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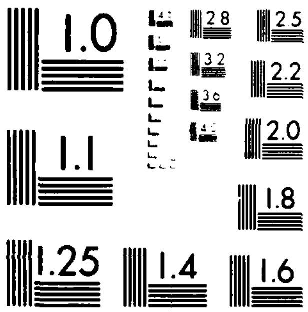

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RESISTANCE OF NAVY SHIPBOARD WORK CLOTHING MATERIALS TO EXTREME HEAT

NAVY CLOTHING
AND
TEXTILE RESEARCH FACILITY

NATICK, MASSACHUSETTS

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Estimates of burn injury potential of Navy work clothing materials have been made by measuring (a) retention of tensile properties during exposure to radiant heat; (b) resistance to ignition; (c) heat transfer during exposure to either radiant heat or flame impingement. Seventeen outerwear fabrics were tested, including polyester, cotton (normal and FR), wool, polyester/cotton, polyester/wool, polyester/rayon, nylon/cotton and Nomex/Kevlar blends of weights ranging from 3.5 to 10.3 oz/yd^2. Four underwear fabrics, both

20. **ABSTRACT (cont)**

woven and knit, made from 100% cotton and 65/35 polyester/cotton were also included, as well as various outerwear/underwear combinations. The analytical work of Alice M. Stoll and her associates was extended to obtain an estimate of burn injury potential from heat transfer data. (U)

FOREWORD

The work described herein was done under contract no. N00140-81-C-BA83 for the Naval Clothing and Textile Research Facility, Natick, Massachusetts. The Technical Representative of the Contracting Officer was Mr. Zelig Kupferman, whose support and advice the authors gratefully acknowledge. The work at Albany International Research Co. was under the general supervision of Norman J. Abbott, Associate Director, and was planned and directed by Meredith M. Schoppee, Senior Research Associate, who also carried out the analysis of heat transfer and estimate of burn injury. John R. Dent was responsible for the computer solutions of the heat transfer equations. All of the laboratory measurements were done by Judith M. Welsford, whose diligence and skill were particularly appreciated.

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I. INTRODUCTION

Work clothing for military personnel is designed primarily to provide comfortable and attractive protective cover during the execution of military duties. Many types of material are employed in standard-issue clothing items depending on the degree of warmth, ruggedness, flexibility and ease of maintenance required in particular circumstances. For personnel confined aboard ship where there is risk of immediate exposure to fire during battle or, for some, the possibility of engine-room catastrophe, the degree of protection offered by clothing items to high levels of heat should be an additional consideration in their choice. In a fire, clothing should provide a protective barrier to the passage of heat while not itself contributing to the potential for burn injury. In order to remain an effective barrier, the clothing material must retain sufficient strength during exposure to withstand the stresses imposed on it by an active wearer running to escape from the vicinity of a fire without losing its integrity.

The investigation described herein explores several aspects of the thermal behavior of a variety of Navy work clothing materials: retention of tensile properties (strength and stiffness) during exposure to radiant heat; resistance to ignition; radiant heat transfer; and heat transfer by direct flame-impingement. The heat transfer and ignition characteristics of both a single layer of various outerwear fabric materials and several outerwear/underwear fabric assemblies have been determined. The tensile properties of outerwear fabrics only were measured during exposure to radiant heat. Measurements were made at radiant heat flux levels to 1.25 $cal/cm^2/sec$ and flame levels of 2.2 $cal/cm^2/sec$.

The seventeen outerwear fabrics in the test group included: 100% polyester, 100% cotton (both untreated and FR treated), and 100% wool fabrics; polyester/cotton, polyester/wool, polyester/rayon and nylon/cotton blended fabrics; and a Nomex/Kevlar fabric (T456 from Dupont). These fabrics range in weight from a low of 3.5 oz/sq yd for a lightweight shirting material to a high of 10.3 oz/sq yd for denim cloth for pants, and include one double-knit construction in the group. The four underwear fabrics supplied for inclusion in 48 fabric outerwear/underwear test assemblies range in weight between 3.0 and 3.6 oz/sq yd and include two 65/35 polyester/cotton blends, one knit and one woven, and two 100% cotton fabrics, also one knit and one woven.

The following report attempts to differentiate the various fabric types represented in the test group in terms of those characteristics most important to thermal protective capacity. It relies heavily in part on similar work carried out on a series of fabrics for the Air Force Materials Laboratory and described in document AFML-TR-77-72[1] to which frequent reference is made.

II. FABRICS INVESTIGATED

A complete description of each of the fabrics in the test group is contained in Table 1. The fabrics, including both outerwear fabrics 1-4 and 6-18 and underwear fabrics 19-22, are grouped in the table according to polymer composition and blend ratio and are further arranged within these categories in order of decreasing weight. Several weave constructions, weave densities and colors are represented in the test group. Fabric weights range from 3.0 to 10.3 oz/sq yd. One doubleknit outerwear fabric, #9, and two jersey knit underwear fabrics #19, #20 are also included.

The tensile strength, rupture elongation and initial modulus of the outerwear fabrics in the incoming condition are reported in Table 2. These properties were determined on an Instron tensile test machine from multiple, one-inch wide raveled strips (one-inch cut strips for knit fabric #9); a specimen gauge length of 13.5 inches and crosshead speed of 20.0 inches/minute were employed. These test conditions were chosen for their suitability in conjunction with subsequent measurements of fabric tensile properties during exposure to high levels of radiant heat. Typical load-elongation diagrams of each of the fabrics tested in both the warp and filling direction are given in Figures 1 through 9. All additional testing of the fabrics was done in the warp direction only.

(Text continued on page 14.)

Table 1. Fabric Construction

Fabric No.	Blend Ratio	Weight (oz/sq yd)	Thickness* (inch)	Weave Pattern	Yarns/Inch (warpxfill)	Air Permeability (cu ft/min/sq ft)	Color	Intended Use
POLYESTER/COTTON BLENDS:								
13	100/0	6.0	0.025	twill	69x60	57	navy	shirts, pants
9	100/0	6.0	0.036	doubleknit	36x24	210	navy	shirts, pants
6	65/35	7.0	0.016	2/1 twill	84x56	45	khaki	pants
16	65/35	5.8	0.016	2/1 twill	125x54	39	navy	shirts, pants
12	65/35	4.8	0.013	mod. basket	92x72	91	med. blue	shirts
15	65/35	4.4	0.011	plain	108x52	90	khaki	shirts
20	65/35	3.4	0.018	jersey knit	32x32	581	white	undershirts
22	65/35	3.0	0.008	plain	144x144	120	white	drawers
7	50/50	6.9	0.017	2/1 twill	108x56	17	white	pants
11	50/50	3.5	0.017	plain	72x46	240	light blue	shirts
1	35/65	10.3	0.029	2/1 twill	70x44	30	denim blue	pants
3	0/100	10.3	0.029	2/1 twill	68x42	23	denim blue	pants
18	0/100 (FR treated)	6.9	0.018	3/1 twill	124x56	30	navy	shirts, pants
19	0/100	3.6	0.019	jersey knit	33x38	307	white	undershirts
21	0/100	3.2	0.011	plain	86x80	90	white	drawers
POLYESTER/WOOL BLENDS:								
8	75/25	6.4	0.017	plain	52x44	44	navy	shirts, pants
2	55/45	6.4	0.018	plain	62x52	34	navy	pants
14	0/100	8.4	0.040	twill	56x50	69	navy	shirts, pants
OTHER BLENDS:								
4	50/50 (nylon/cotton)	9.3	0.023	sateen	122x76	6	navy	pants
10	65/35 (polyester/rayon)	5.9	0.017	plain	56x48	104	navy	shirts
17	95/5 (T456) (Nomex/Kevlar)	4.6	0.015	plain	72x48	79	olive green	shirts, pants

*Measured at 0.0312 psi

Table 2. Tensile Properties of Outerwear Fabrics

Fabric No.	Blend Ratio	Weight (oz/sq yd)	Yarns/Inch (warpxfill)	Modulus (lbs/inch/unit strain)		Rupture Elongation (%)		Rupture Load (lbs/inch)	
				Warp	Fill	Warp	Fill	Warp	Fill
POLYESTER/COTTON BLENDS:									
13	100/0	6.0	69x60	620	780	40	20	164	77
9	100/0	6.0	36x24	90	70	99	127	54	57
6	65/35	7.0	84x56	1870	730	21	32	134	89
16	65/35	5.8	125x54	1380	660	23	25	127	49
12	65/35	4.8	92x72	1570	380	22	40	90	55
15	65/35	4.4	108x52	1220	560	22	24	104	42
7	50/50	6.9	108x56	1420	790	14	16	146	73
11	50/50	3.5	72x46	1370	350	8	26	59	41
1	35/65	10.3	70x44	1400	610	33	19	181	69
3	0/100	10.3	68x42	1340	1030	31	14	138	76
18	0/100 (FR treated)	6.9	124x56	1890	950	11	11	103	42
POLYESTER/WOOL BLENDS:									
8	75/25	6.4	52x44	520	520	19	18	60	53
2	55/45	6.4	62x52	520	520	33	34	85	81
14	0/100	8.4	56x50	310	150	22	30	33	26
OTHER BLENDS:									
4	50/50 (nylon/cotton)	9.3	112x76	975	1000	27	26	155	147
10	65/35 (polyester/rayon)	5.9	56x48	610	370	25	37	93	73
17	95/5 (T456) (Nomex/Kevlar)	4.6	72x48	900	740	30	26	115	71

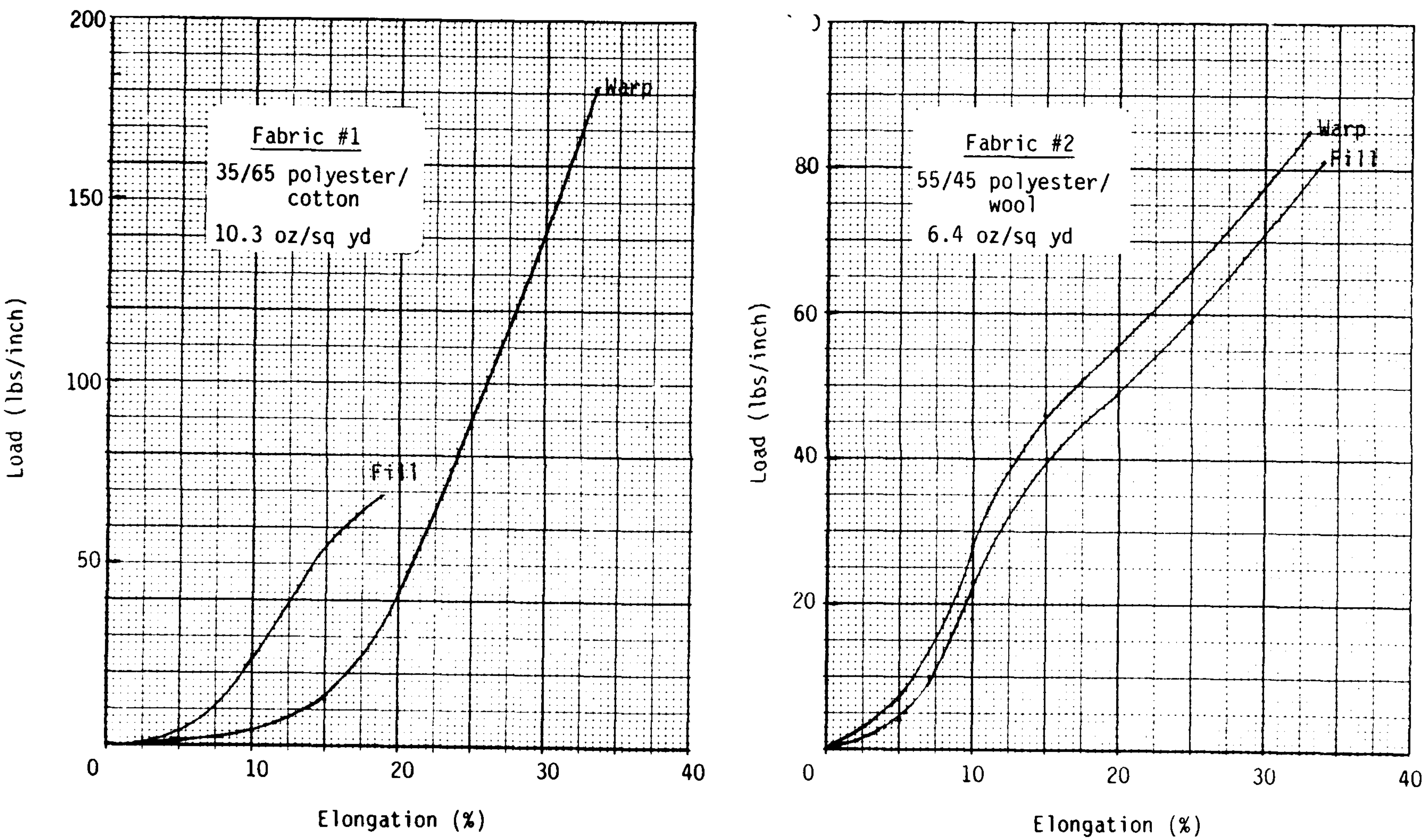


Figure 1. Typical Fabric Load-Elongation Diagrams at 20°C, 65%RH: Fabrics #1 and #2

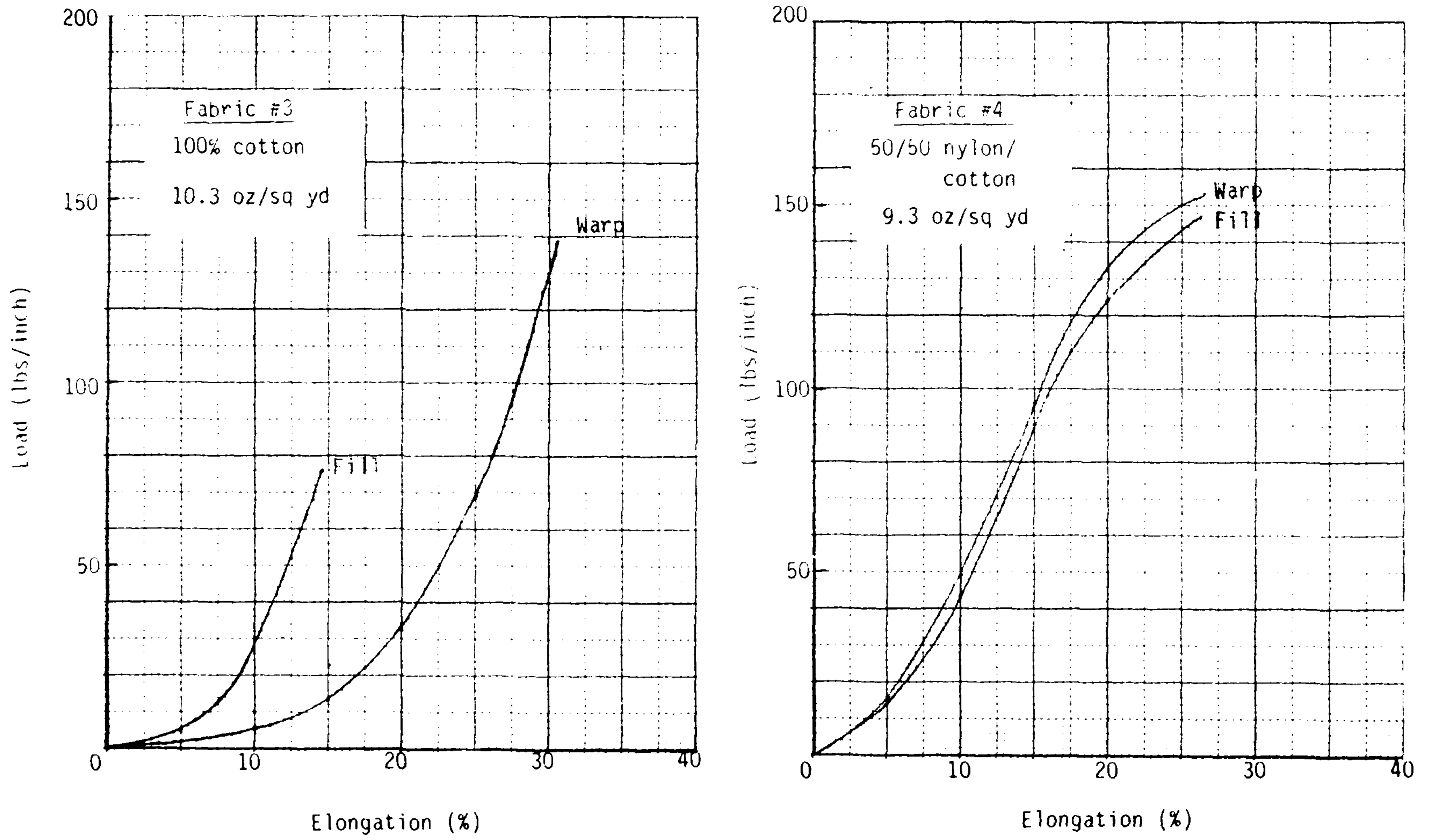


Figure 2. Typical Fabric Load-Elongation Diagrams at 20°C, 65%RH: Fabrics #3 and #4

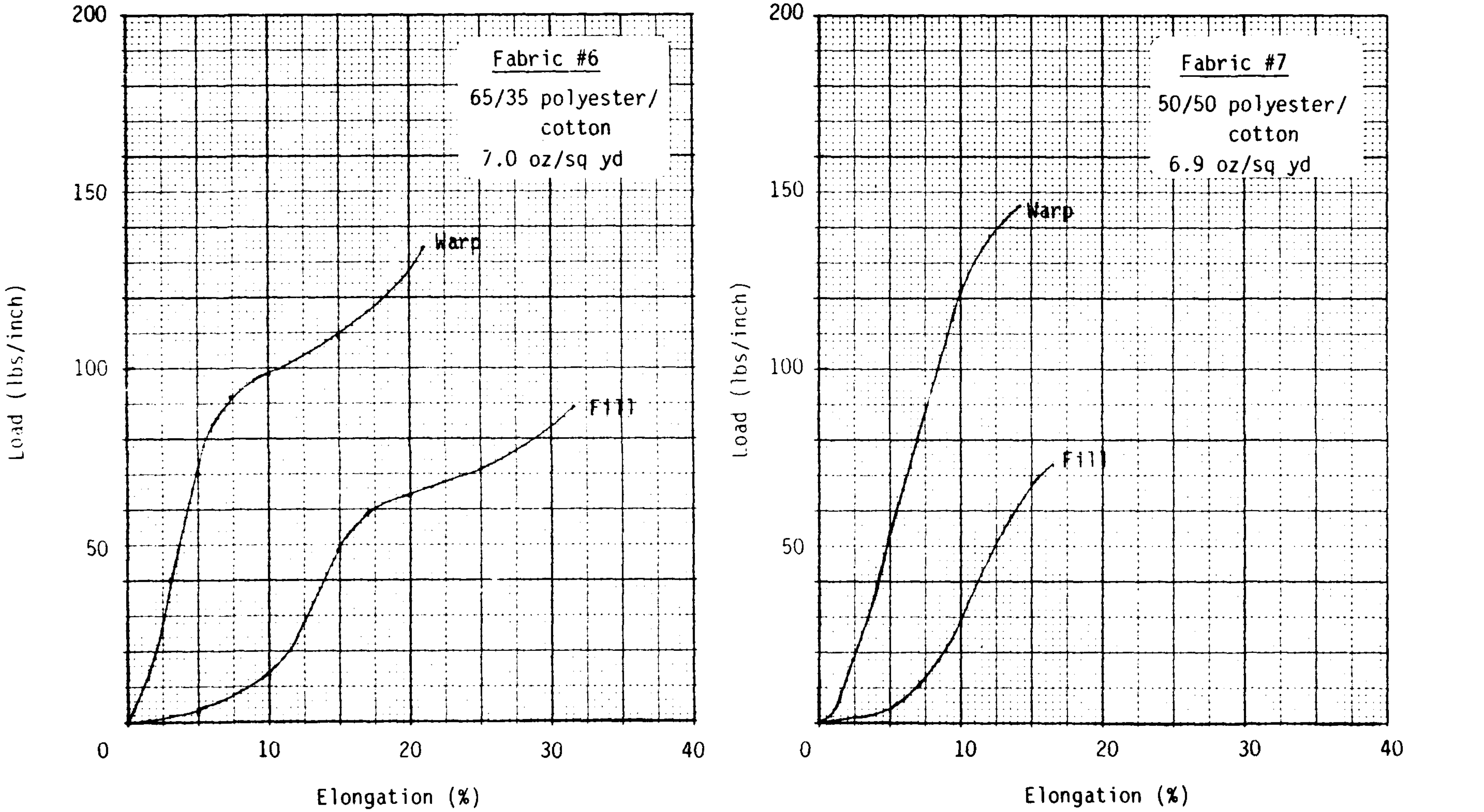


Figure 3. Typical Fabric Load-Elongation Diagrams at 20°C, 65%RH: Fabrics #6 and #7

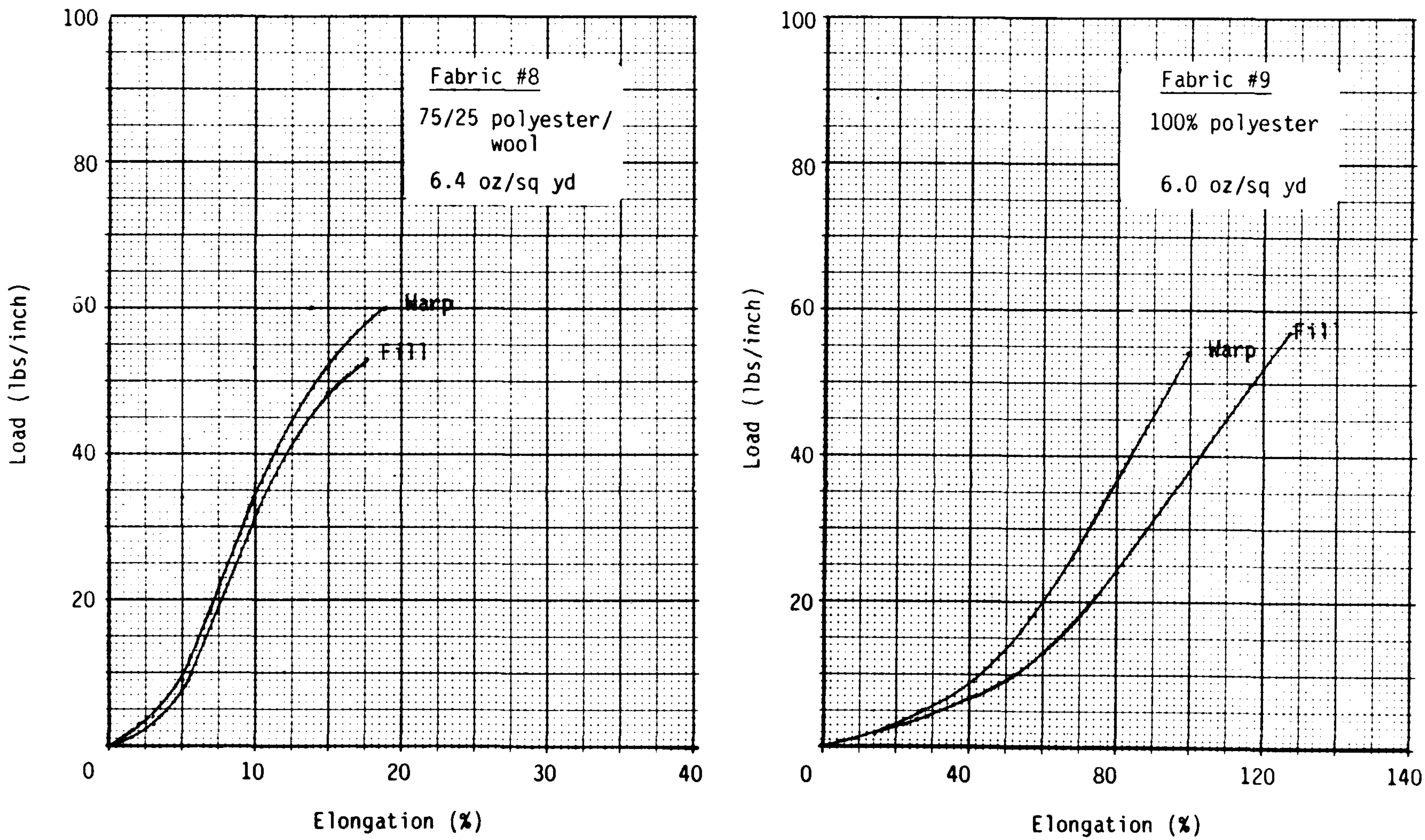


Figure 4. Typical Fabric Load-Elongation Diagrams at 20°C, 65%RH: Fabrics #8 and #9

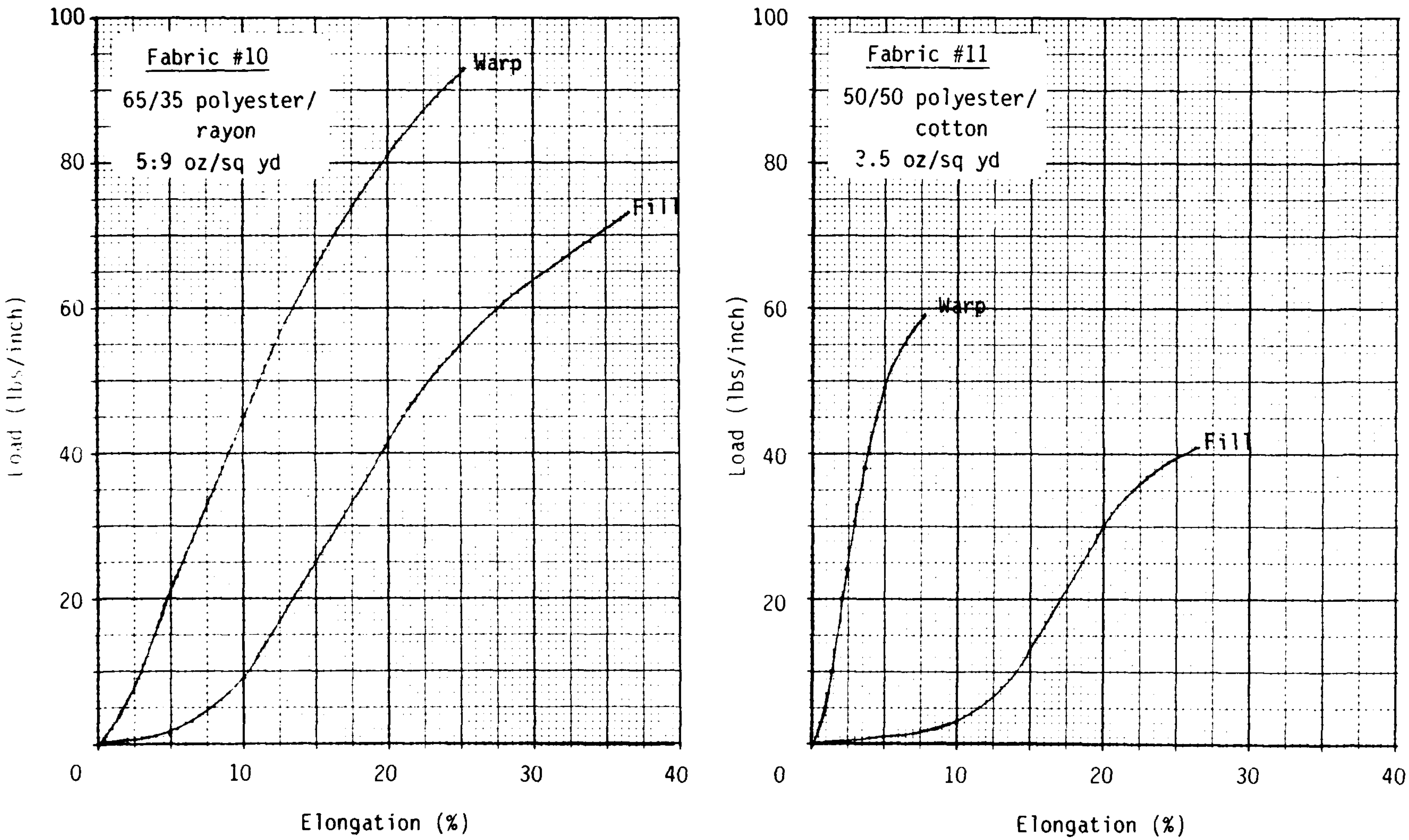


Figure 5. Typical Fabric Load-Elongation Diagrams at 20°C, 65%RH: Fabrics #10 and #11

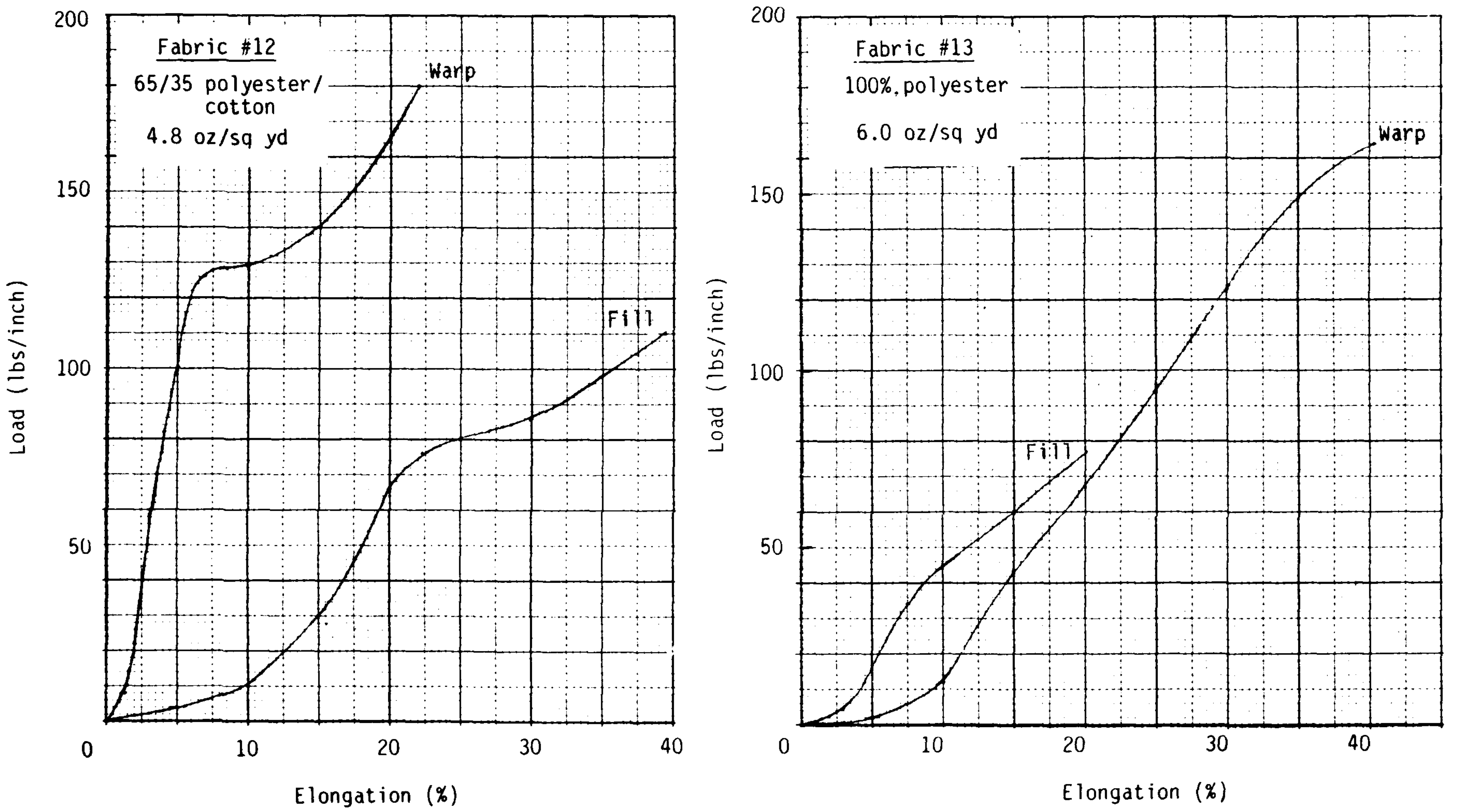


Figure 6. Typical Fabric Load-Elongation Diagrams at 20°C, 65%RH: Fabrics #12 and #13

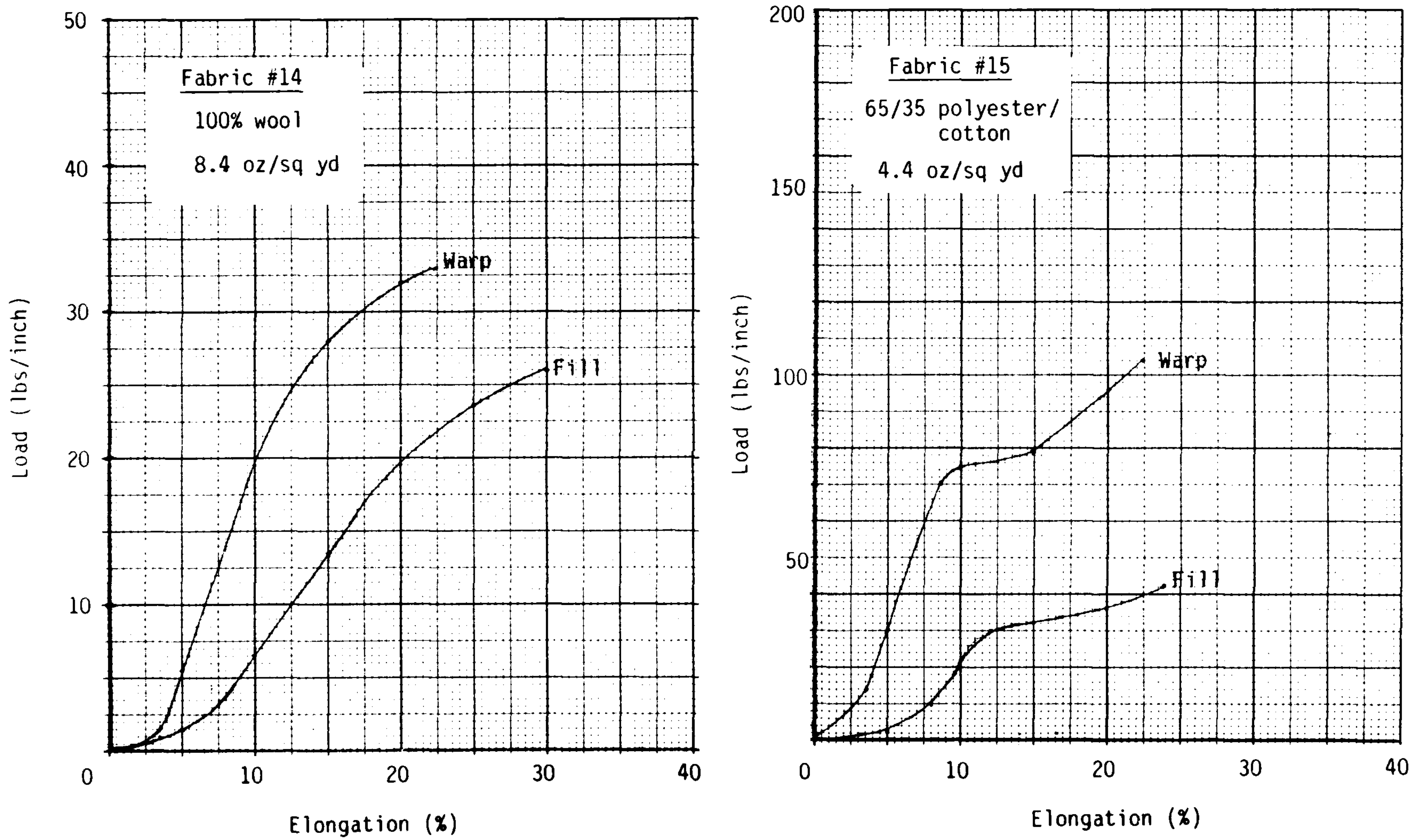
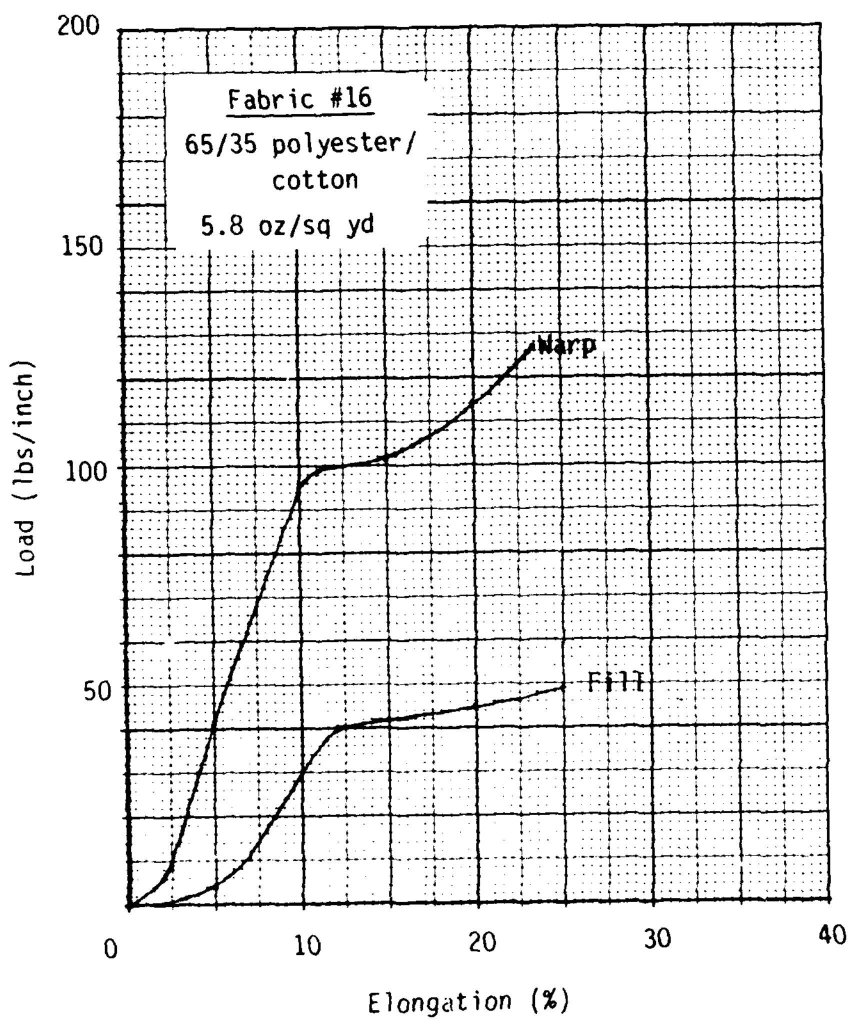


Figure 7. Typical Fabric Load-Elongation Diagrams at 20°C, 65%RH: Fabrics #14 and #15



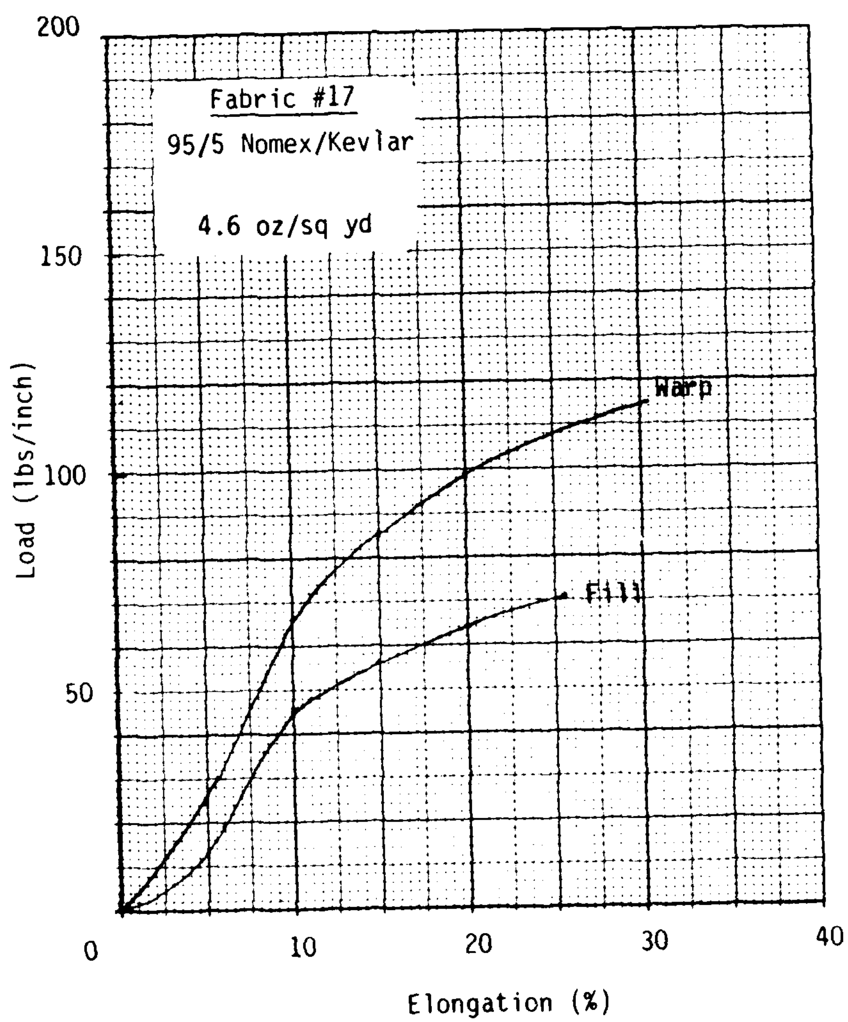


Figure 8. Typical Fabric Load-Elongation Diagrams at 20°C, 65%RH: Fabrics #16 and #17

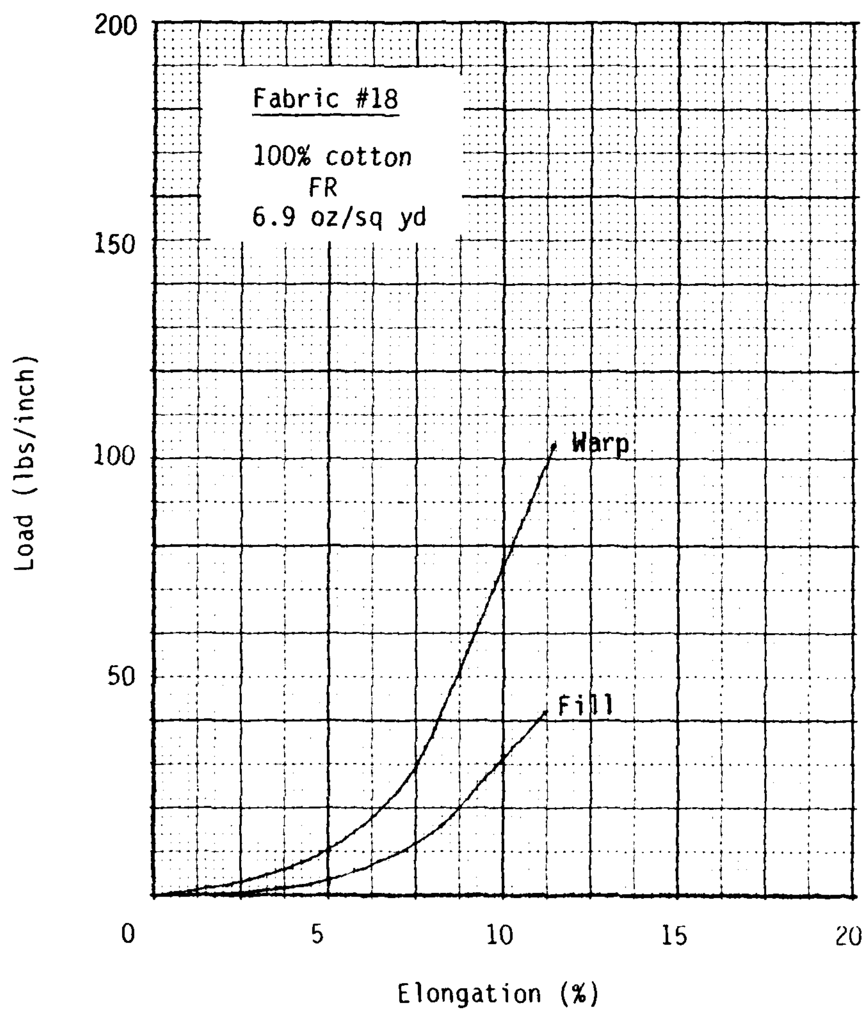


Figure 9. Typical Fabric Load-Elongation Diagram at 20°C, 65%RH: Fabric #18

III. EXPOSURE TO BILATERAL RADIANT HEAT

A. Laboratory Simulation of a Fire Environment

Large fueled fires behave essentially like blackbody radiators[2,3]. The temperature within such fires can approach 1200°C, although an average value of internal radiative heat flux between 2.2 cal/cm²/sec[2], corresponding to a blackbody temperature of 860°C, and 3.7 cal/cm²/sec[3], corresponding to a temperature of 1000°C, are generally accepted. In order to simulate the radiation characteristics of a large fire in the laboratory, a radiant heat source is needed which is capable of attaining in a controlled fashion both temperature and heat flux levels of equivalent intensity to those in a fire. In addition to the requirements of reproducing the radiative environment of a large fire, a laboratory test system designed to monitor the deterioration of fabric mechanical properties during exposure to radiant heat must be suitable for use in conjunction with laboratory tensile testing machines.

A testing system has been developed[1] in which the radiative thermal environment of a large fire is duplicated reasonably well and which is adaptable to Instron use so that the tensile properties of test fabric strips can be monitored during short term exposures to high heat fluxes in air. In our experimental set-up, diagrammed in Figure 10 and photographed in Figure 11, a pair of facing quartz heater panels capable of achieving internal temperatures of 1200°C are mounted in a test chamber which is itself attached to the crosshead of an Instron tensile test machine. Fabric test strips are mounted in split cylinder jaws which slip into special jaw holders attached to the Instron load cell and crosshead respectively. The heater surfaces are previously brought to equilibrium temperature and at the start of exposure either the fabric is slid quickly into place by means of a track and plunger system or, as the system is presently configured, the heaters themselves are pulled rapidly along a track to surround the test specimen already in place. The onset of exposure is virtually instantaneous, the duration of exposure is precisely known, and subsequent mechanical stressing is performed quickly so that information on fabric tensile properties can be generated during the period of rapid temperature rise as well as after thermal equilibrium has been reached.

The mechanical test conditions employed include a crosshead traverse speed of 20 inches/minute in conjunction with a 13.5 inch specimen gauge length resulting in a strain rate of approximately 150%/minute. Specimen insertion and activation of the Instron crosshead can be accomplished within one second. The shortest exposure time at which tensile strength can be measured is that time required to reach the rupture elongation of the specimen at the strain rate of 150%/minute: typically 3 to 10 seconds after the initiation of exposure. Specimens may also be left in place between the heater surfaces for longer periods before tensile testing is begun if a longer exposure is desired.

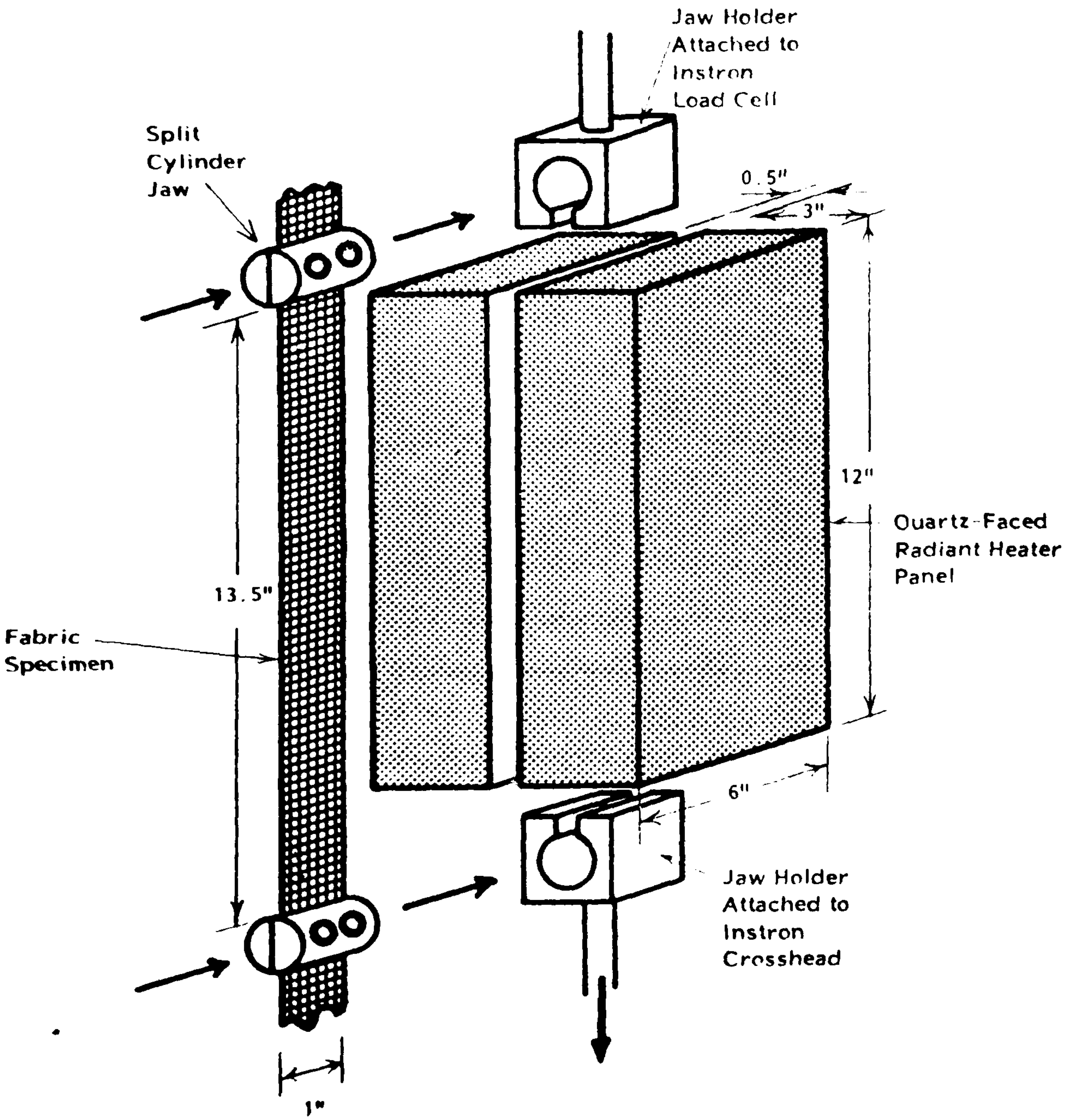


Figure 10. Test Configuration for Exposure of Fabric Specimen to Bilateral Radiant Heat

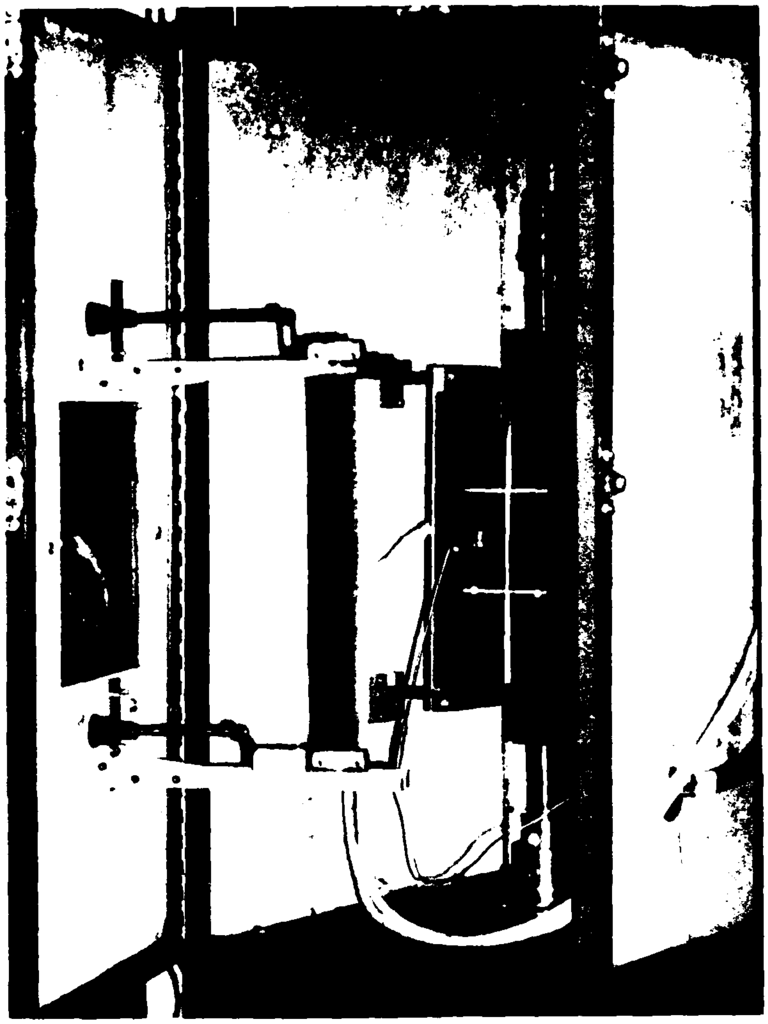


Figure 11. Quartz-Faced Radiant Heater Panels and Fabric Specimen in Test Chamber

The thermal output of each of the quartz-faced heater panels has been measured individually in a unilateral configuration using a water-cooled copper calorimeter. The current calibration for each single heater is compared in Figure 12 with the original calibration made in 1976[1]; as seen, the thermal output as a function of heater temperature has decreased with time and use. The Stefan-Boltzman equation for flux density Q, emitted from a grey, diffuse surface[1]:

$$Q = \varepsilon(T)\sigma T^4 \tag{1}$$

allows calculation of the emissivity $\varepsilon(T)$ of the quartz heater surfaces as a function of measured temperature (T) in degrees Kelvin and heat flux (Stefan-Boltzman constant, $\sigma = 1.354 \times 10^{12}$ cal/cm^2/sec/$^{\circ}$K^4). The results of this calculation are plotted in Figure 13 where current values of emittance are compared with the original values determined when the heaters were new. The change in surface optical characteristics of the quartz panels is probably the result of a gradual accumulation of particulates from smoking and burning specimens and a change in the vitrescense of the fused-quartz faces.

Using the newly determined values of heater emissivity, the initial radiative heat flux <u>absorbed</u> by a fabric specimen when placed between the closely spaced pair of facing heaters can be calculated from the following relationship if the fabric emissivity is known[1]:

$$Q = \frac{2\sigma(T_1{}^4 - T_2{}^4)}{\dfrac{1}{\varepsilon_1(T_1)} + \dfrac{1}{\varepsilon_2(T_2)} - 1} \tag{2}$$

where Q is the heat flux absorbed by the specimen

T_1 is the heater surface temperature ($^{\circ}$K)

T_2 is the temperature of the specimen ($^{\circ}$K)

$\varepsilon_1(T_1)$ is the emissivity of the quartz surface at temperature T_1

$\varepsilon_2(T_2)$ is the emissivity of the specimen surface at temperature T_2.

Values of fabric absorptance [absorptance = emittance for grey bodies[1]] taken from the literature[3,4] and plotted in Figure 14 have been used with Eq 2 to estimate the <u>initial</u> bilateral radiant heat flux <u>absorbed</u> by a test specimen. (Initial flux is given since it is maximum. As the temperature T_2 of the specimen approaches the temperature T_1 of the heaters, it can be seen from the form of Eq 2 that absorbed flux Q decreases). The results of this calculation are presented in Figure 15 where they are compared to those resulting from the original calibration of the heaters and with the heat flux that would be absorbed from a blackbody source ($\varepsilon_1(T_1) = 1$) at the same temperature. The thermal characteristics of the heaters in the bilateral configuration still approximate reasonably well those of a blackbody source both in terms of the heat flux-temperature relationship of Figure 15 and with respect to the wavelength of emitted radiation[1,5] as shown in Figure 16.

(Text continued on page 23.)

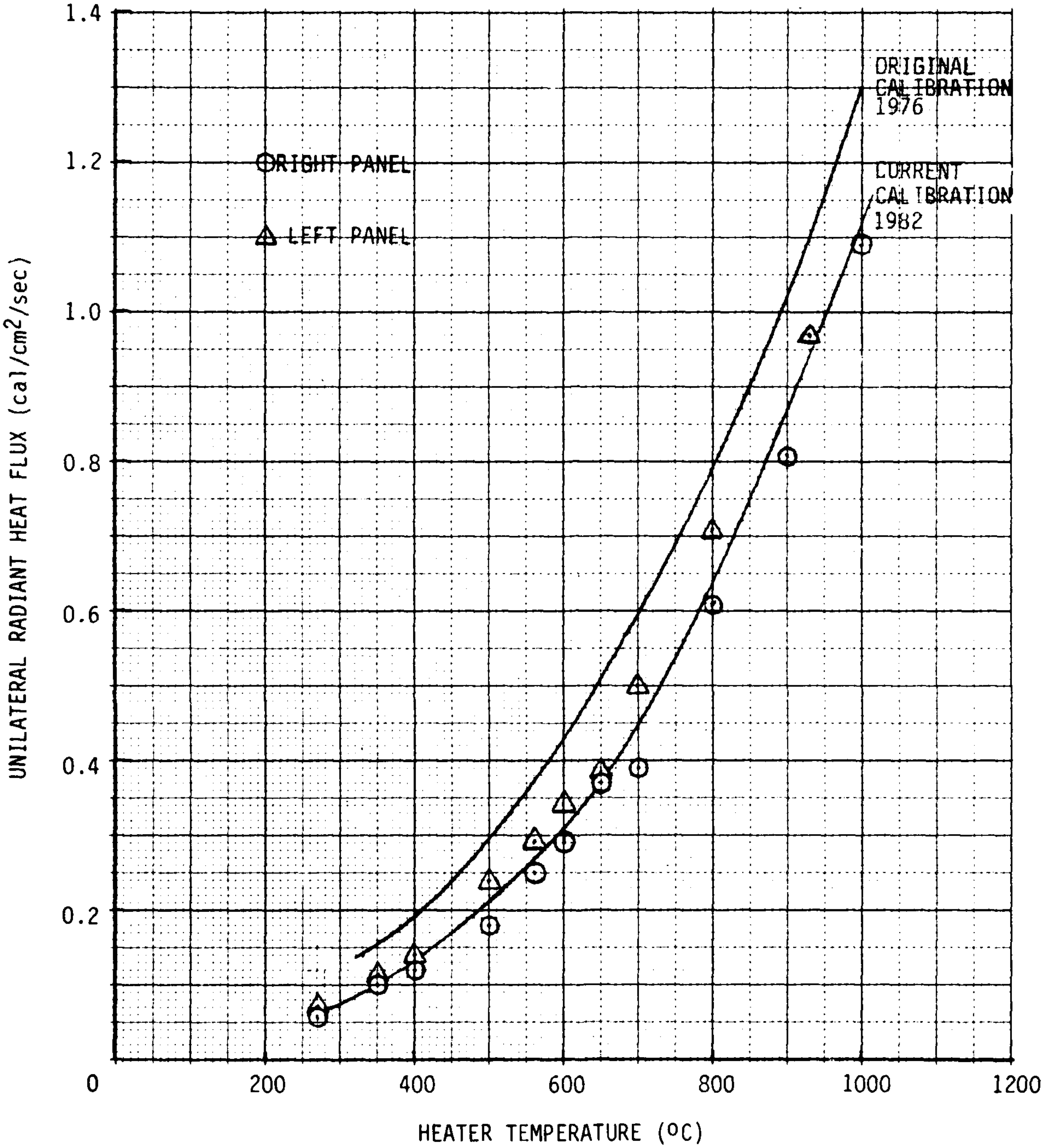


Figure 12. Recalibration of Individual Quartz-Faced Radiant Heater Panels

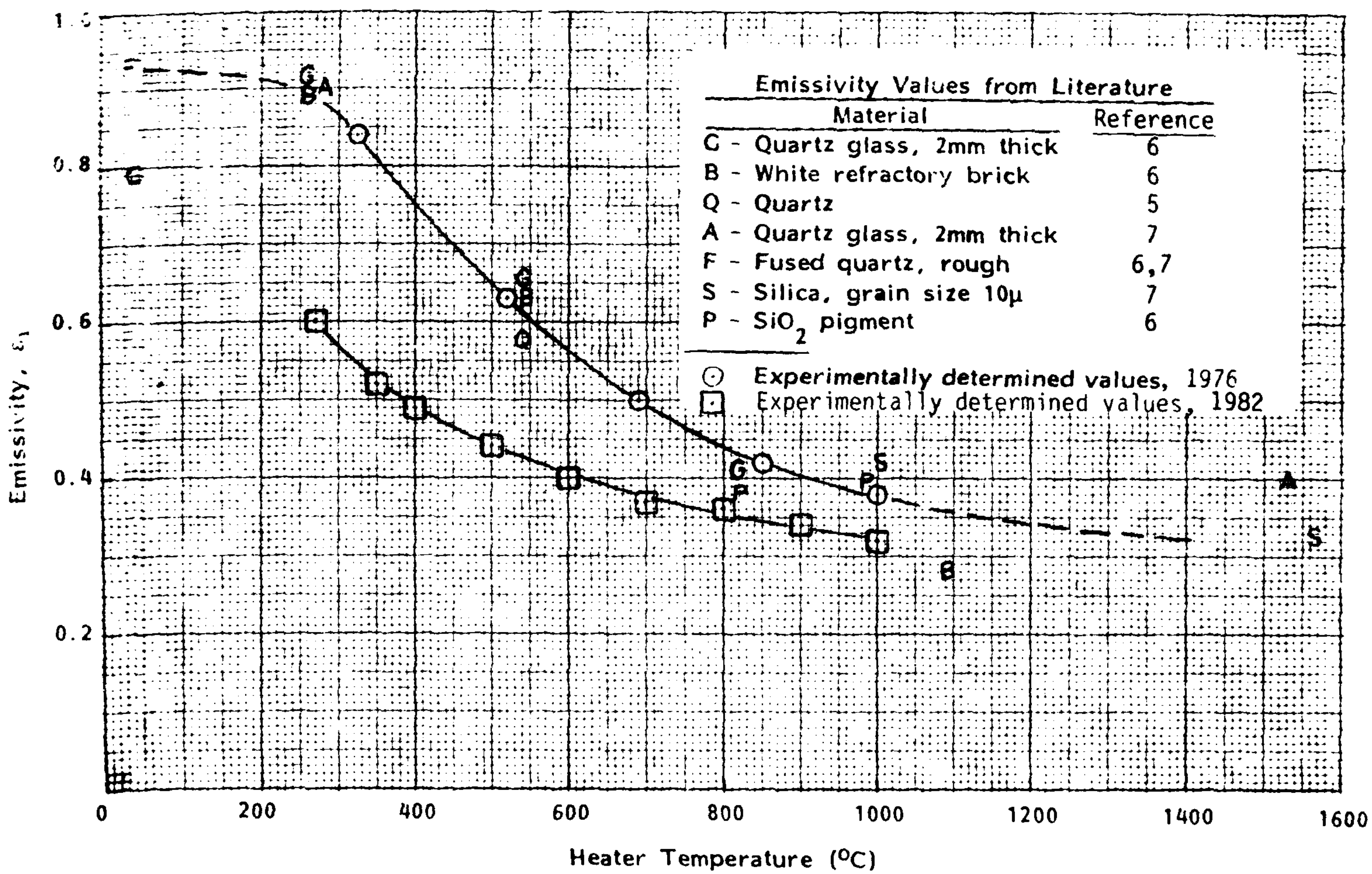


Figure 13. *Emissivity of Quartz-Faced Radiant Heater Panels*

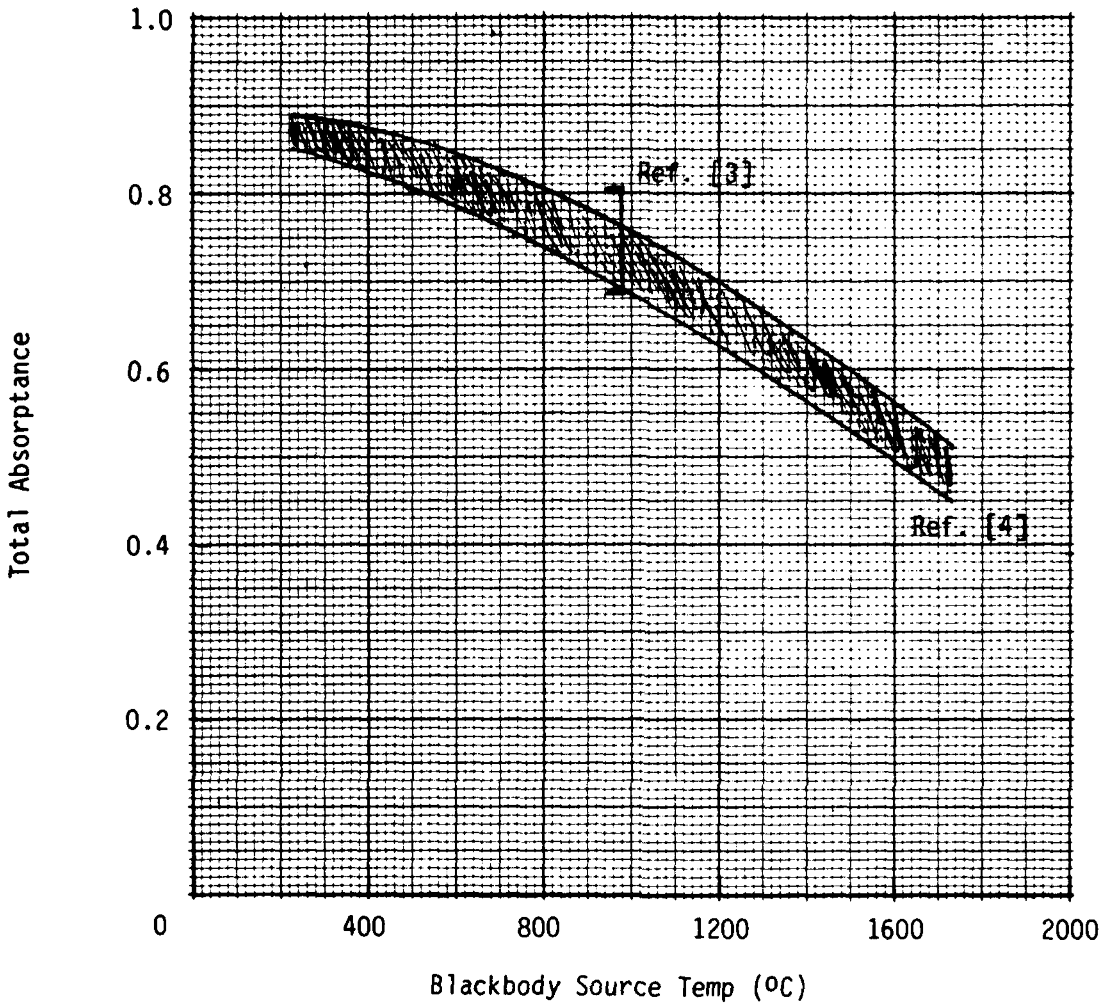


Figure 14. Absorptance of Fabrics Exposed to Blackbody Source

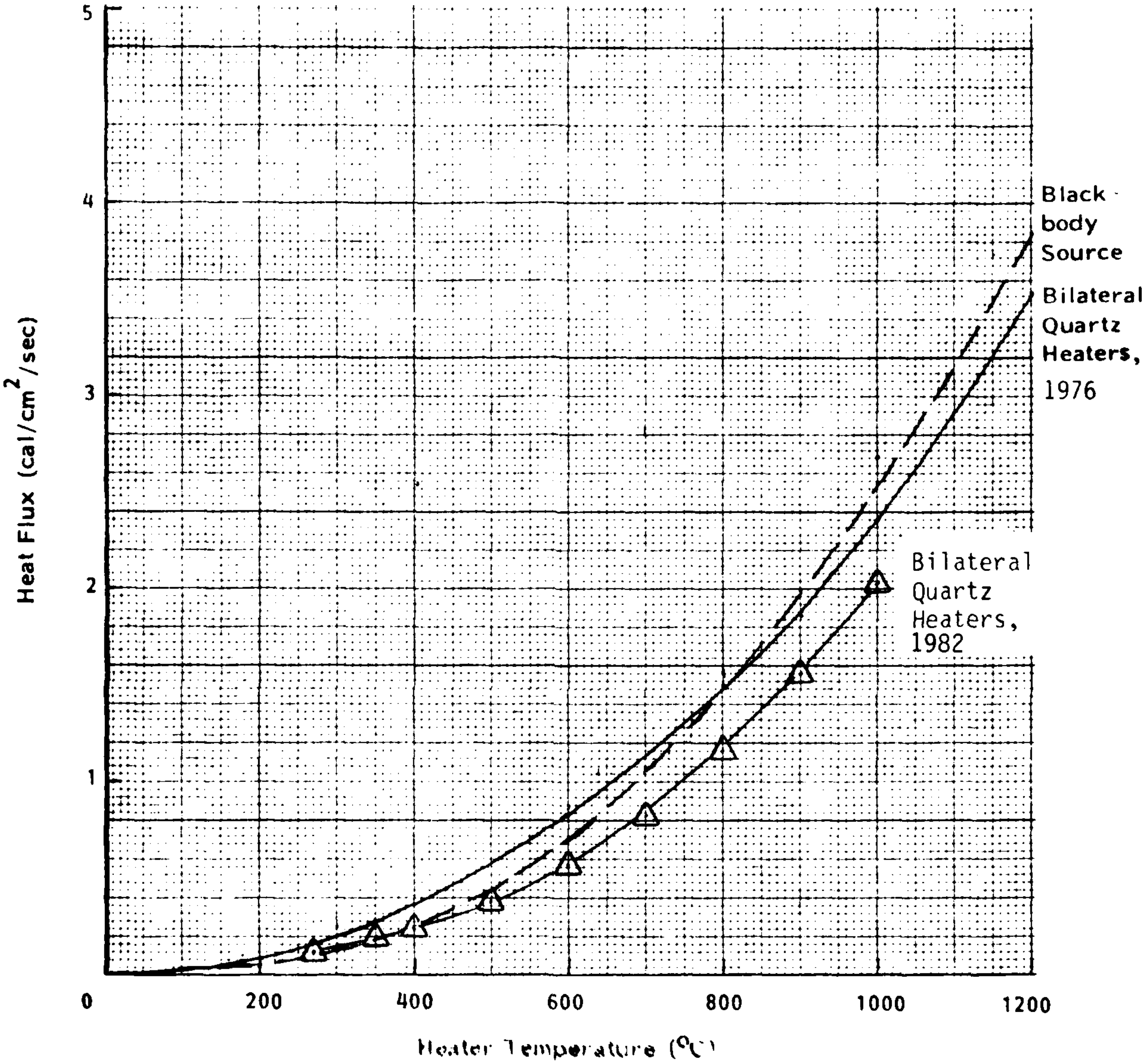


Figure 15. Initial Bilateral Radiant Heat Flux Absorbed by Fabric Specimen

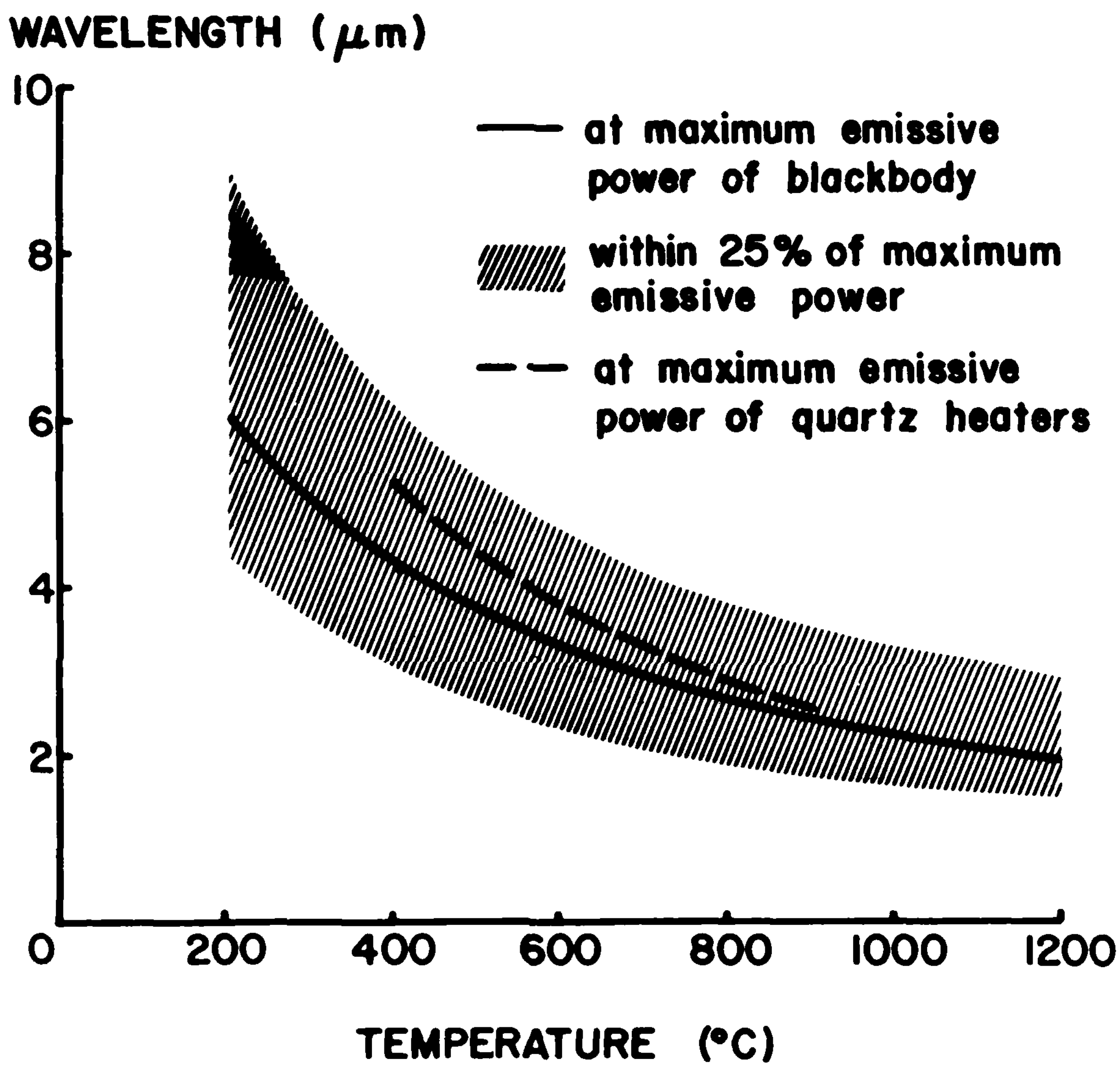


Figure 16. Comparison of Dominant Wavelengths Emitted from a Blackbody and from the Quartz Heater Panels

During exposure of a fabric specimen to bilateral radiant heat, the temperature of the fabric increases rapidly during the initial stages of exposure and then more gradually achieves a maximum equilibrium temperature nearly equal to the temperature of the heater surfaces. In our system the heater surface temperature is generally within 10 to 20°C of the measured internal temperature of the heaters. The time required to reach equilibrium temperature can be estimated as outlined in Ref. 1, Eq 7 in terms of fabric weight per unit area, emissivities of the fabric and heater surfaces, and temperature of the heater surface. The results of this calculation for both original and current values of heater surface emissivity are shown in Figure 17 for a non-melting fabric weighing 6 oz/sq yd. The effect of the current lower emissivity of the heater surfaces is principally to slow the specimen heating rate so that a longer time is required for the specimen to reach the equilibrium temperature of the heater surfaces. Thus, it can be seen that specification of <u>either</u> absorbed heat flux <u>or</u> equilibrium temperature is <u>insufficient</u> to describe the short-term thermal history of materials exposed to high radiant heat flux levels: <u>both source temperature and heat flux level must be specified</u> if transient properties are of interest; specimen equilibrium temperature is sufficient if only the steady-state condition is being investigated.

The tensile properties of irradiated fabrics have been shown to depend principally on their temperature at a given time during exposure[1]; temperature, in turn, is determined by the <u>net</u> heat flux absorbed by the specimen independent of the exposure configuration, whether bilateral or unilateral[1]. Bilateral radiation for the characterization of fabric properties as a function of exposure conditions has the advantage that the net heat flux absorbed by the specimen and the specimen equilibrium temperature are more precisely known and more uniform than during unilateral exposure: heat losses from a non-irradiated surface need not be considered in the bilateral configuration.

B. Fabric Tensile Properties During Exposure to Bilateral Radiant Heat

Although the quartz heater panels used in this investigation of fabric properties are capable of attaining the high levels of radiant heat found in a large fire (2-3 cal/cm^2/sec), it had earlier[1] been determined that even the "high-temperature" materials could not withstand fluxes greater than approximately 1.3 cal/cm^2/sec without losing all strength and igniting within the first second or two of exposure. Therefore, in order to be able to differentiate between fabrics, their properties at less severe levels of exposure were determined.

The tensile strength retention and modulus of each of the 17 outerwear fabrics were measured during bilateral exposure to radiant heat at the following exposure intensities:

270°C (0.1 cal/cm^2/sec);
350°C (0.2 cal/cm^2/sec);
400°C (0.25 cal/cm^2/sec);
500°C (0.4 cal/cm^2/sec); and
560°C (0.5 cal/cm^2/sec).

These temperatures were chosen to correspond with heater temperatures used in earlier work[1].

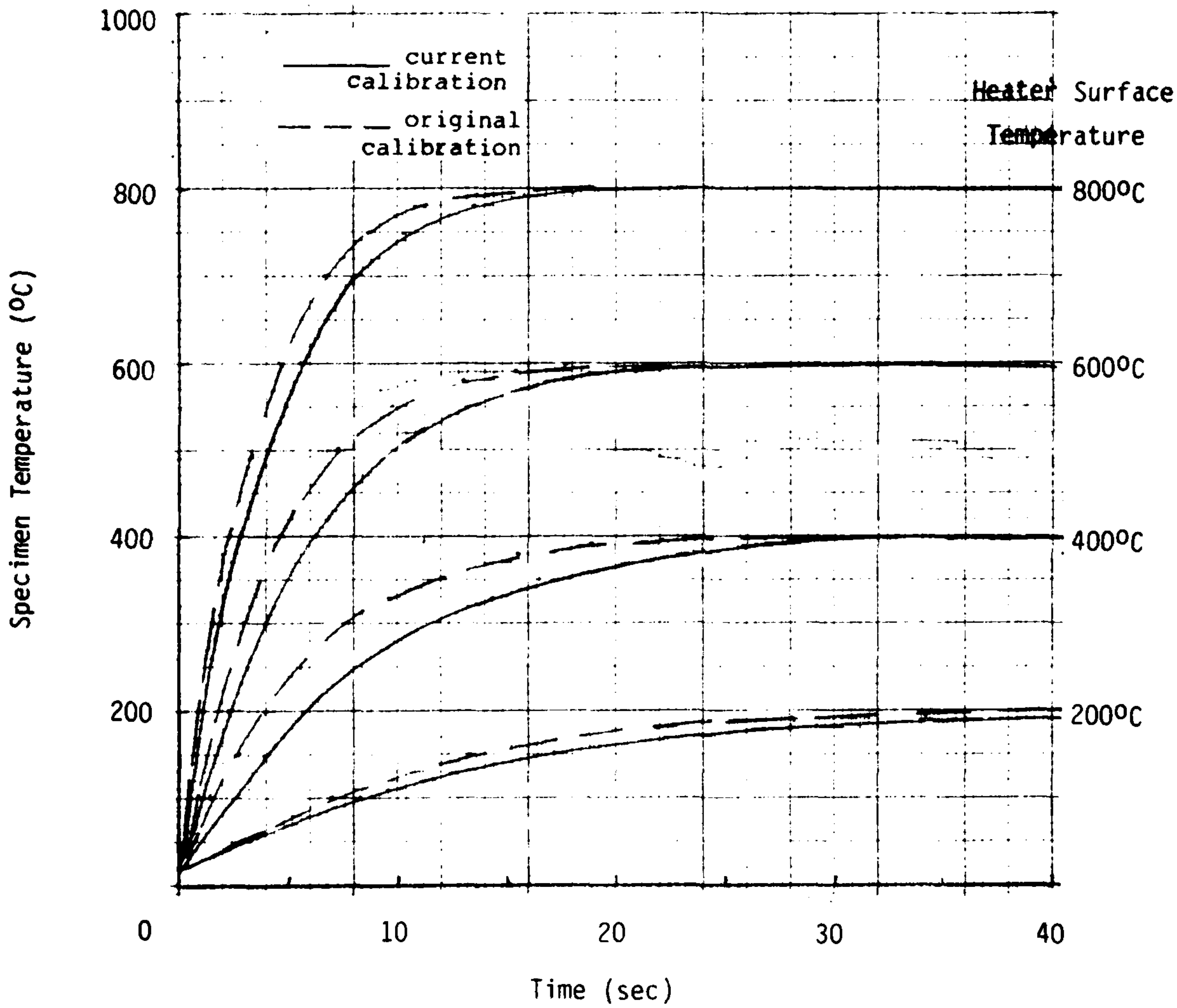


Figure 17. Estimated Specimen Temperature During Bilateral Exposure to Quartz Heater Panels: Specimen Weight, 6 oz/sq yd

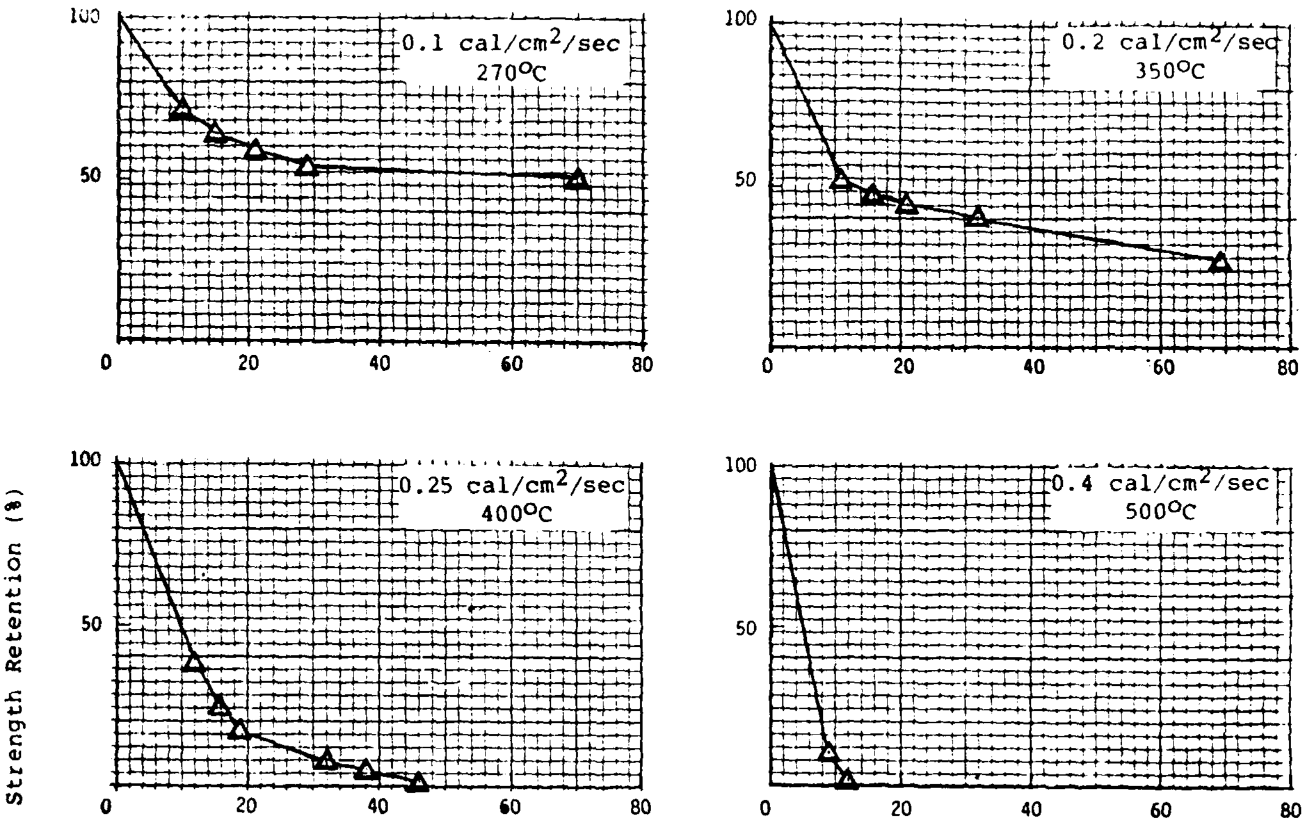
The average values of fabric strength expressed as a percentage of original strength for various times of exposure at each heat flux condition are plotted in Figures 18a through 34a for fabrics 1-4 and 6-18, respectively; individual test results are documented in Appendix Table 1. Similarly, average values of fabric modulus are plotted in Figures 18b through 34b and individual values are listed in Appendix Table 1. The values of strength retention are given at total exposure time to rupture: this time includes both the dwell time prior to the start of crosshead motion and the time required to rupture the specimen after the onset of loading.

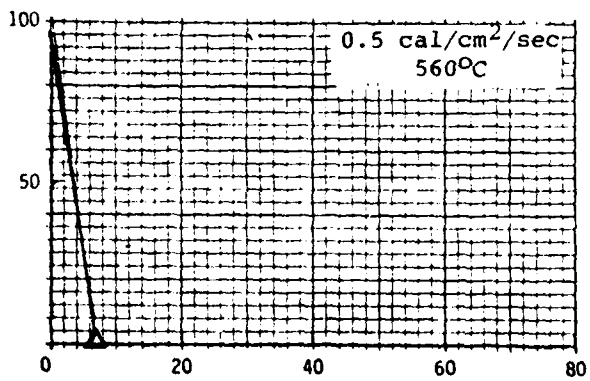
The modulus values given represent the maximum slope of the load-elongation curves. These values are somewhat in error, however, because a portion of the specimen length is located outside of the high-temperature region between the facing heater panels. As discussed in Ref. 1, pp 47 and 71-74, the true modulus of the specimen during exposure is related to the ratio of the modulus measured directly from the Instron load-elongation diagram to the original modulus at ambient temperature. For example, if the measured modulus during exposure is one half of the original modulus, the true modulus may be as low as 85% of the measured value; similarly, if the measured modulus is one tenth of the original level, the actual modulus may be only 76% of the measured value. Notwithstanding this error, the approximate modulus, as measured, can be a valuable indicator of the occurrence of physical and chemical changes within the material with increasing temperature.

As seen in Figures 18a through 34a, at the lower heat intensities, many of the materials exhibit a rapid decrease in strength during the initial few seconds of exposure followed by a more gradual decrease until ultimately an equilibrium level of strength is attained. This is the general type of behavior that would be expected on the basis of the shape of the estimated time-temperature curves shown in Figure 17. For a hypothetical strength-temperature relationship such as that depicted in Figure 35, strength retention as a function of time for a 6 oz/sq yd fabric that contains neither particularly large amounts of sorbed water nor a significant thermoplastic fraction should display the trends illustrated by the theoretical curve in Figure 36 which has been determined by combination of the information in Figures 17 and 35. Heavier weight fabrics would require a proportionately longer time to reach equilibrium and lighter weight fabrics, a shorter time. The strength retention curves of nearly all of the fabrics tested exhibit this general shape at 270°C. Some minor perturbations in the curves for fabrics 3 (100% cotton, 10.3 oz/sq yd) and 14 (100% wool, 8.4 oz/sq yd) may be attributed to a one or two second delay resulting from vaporization of the relatively large amounts of sorbed water held by these materials.

At 350°C and 400°C, melting of the polyester and nylon components of some of the fabrics causes precipitous loss of all strength and, in the case of the heavier fabrics, departure from the smooth shape of the theoretical curve. (See in particular Figures 22a, 23a, 26a, 29a and 32a). For example, at heater surface temperatures of 400°C, the additional time required to melt the polymer in a 50/50 polyester or nylon/cotton blended fabric weighing 6.0 oz/sq yd may be computed from heats of fusion of polyester (31 cal/g) and nylon 6,6 (45 cal/g)[8]; the estimated delay in further temperature rise when the fabric has achieved the melting temperature of 260°C is 2 seconds for a polyester blend and 3 seconds for a nylon 6,6 blend. For greater fractions of polyester or nylon or heavier fabrics, the delay would be proportionately longer: for a 65% polyester fabric weighing 10 oz/sq yd, the delay would be approximately 3 seconds.

(Text continued on page 60.)





Heat Flux ($cal/cm^2/sec$)	Time to Ignition (sec) Range	Average
0.1	---	---
0.2	---	---
0.25	No ignition, 2 min	
0.4	25-28	27
0.5	9-10	9
0.6	4-8	6
0.7	4-6	5

Duration of Exposure (sec)

Figure 18a. Strength Retention of Fabric #1 (35/65 polyester/cotton blend, 10.3 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat

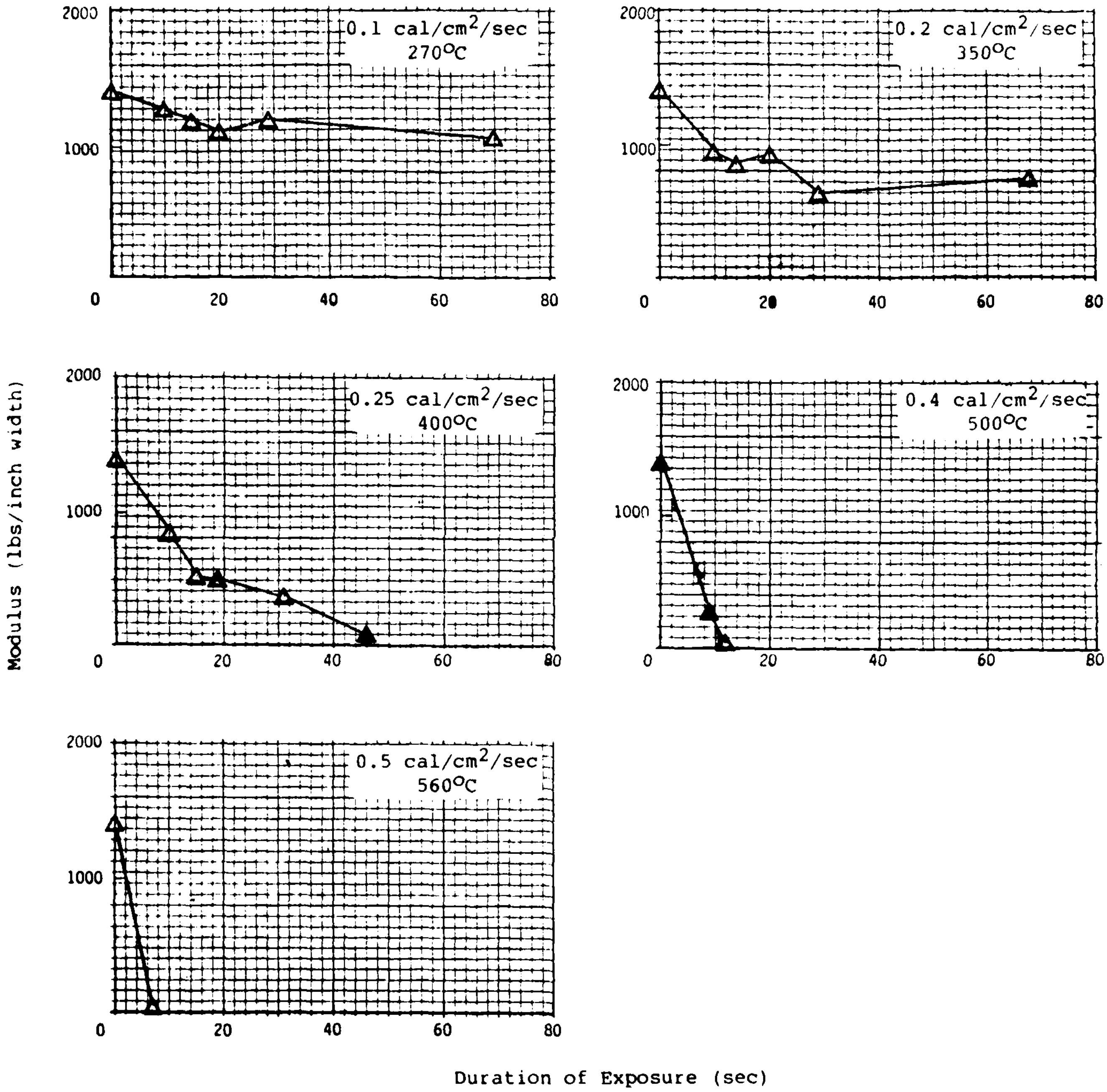
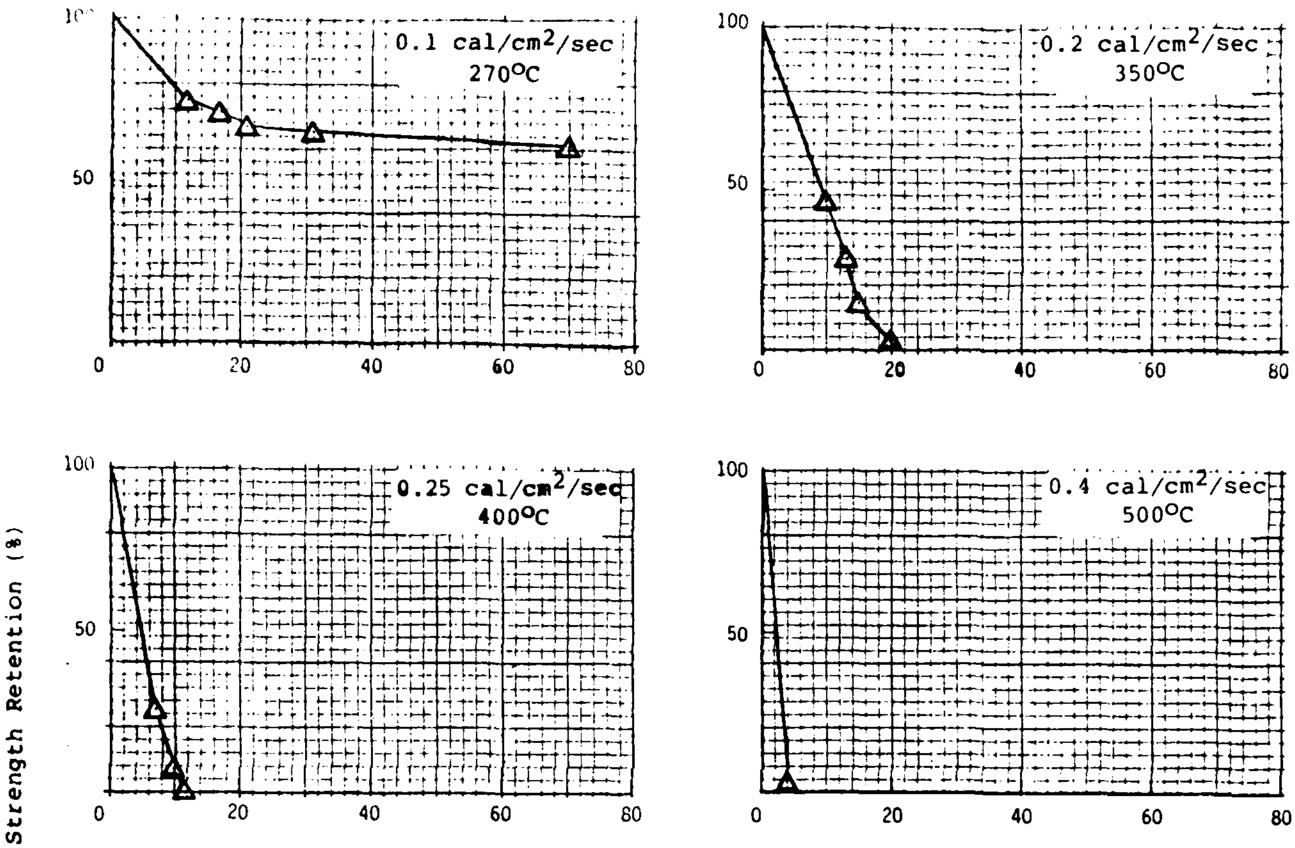
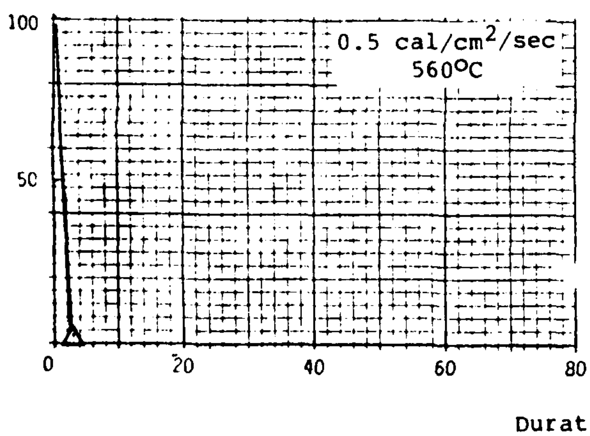


Figure 18b. Modulus of Fabric #1 (35/65 polyester/cotton blend, 10.3 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat





Heat Flux ($cal/cm^2/sec$)	Time to Ignition (sec) Range	Average
0.1	---	---
0.2	---	---
0.25	No ignition, 2 min	
0.4	65-90	80 (glow only)
0.5	18-50	25
0.6	13-18	16
0.7	---	4

Figure 19a. Strength Retention of Fabric #2 (55/45 polyester/wool, 6.4 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat

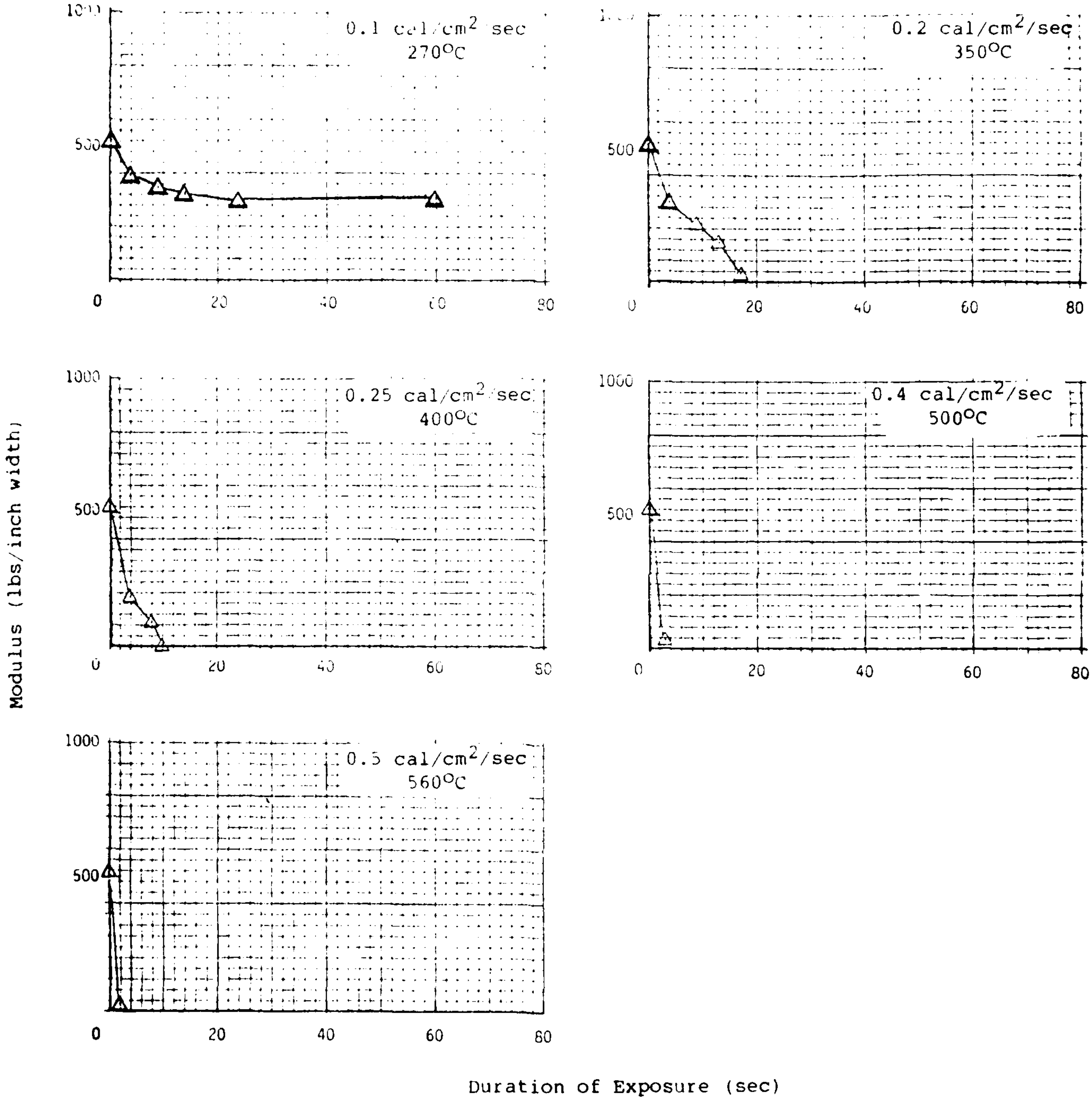
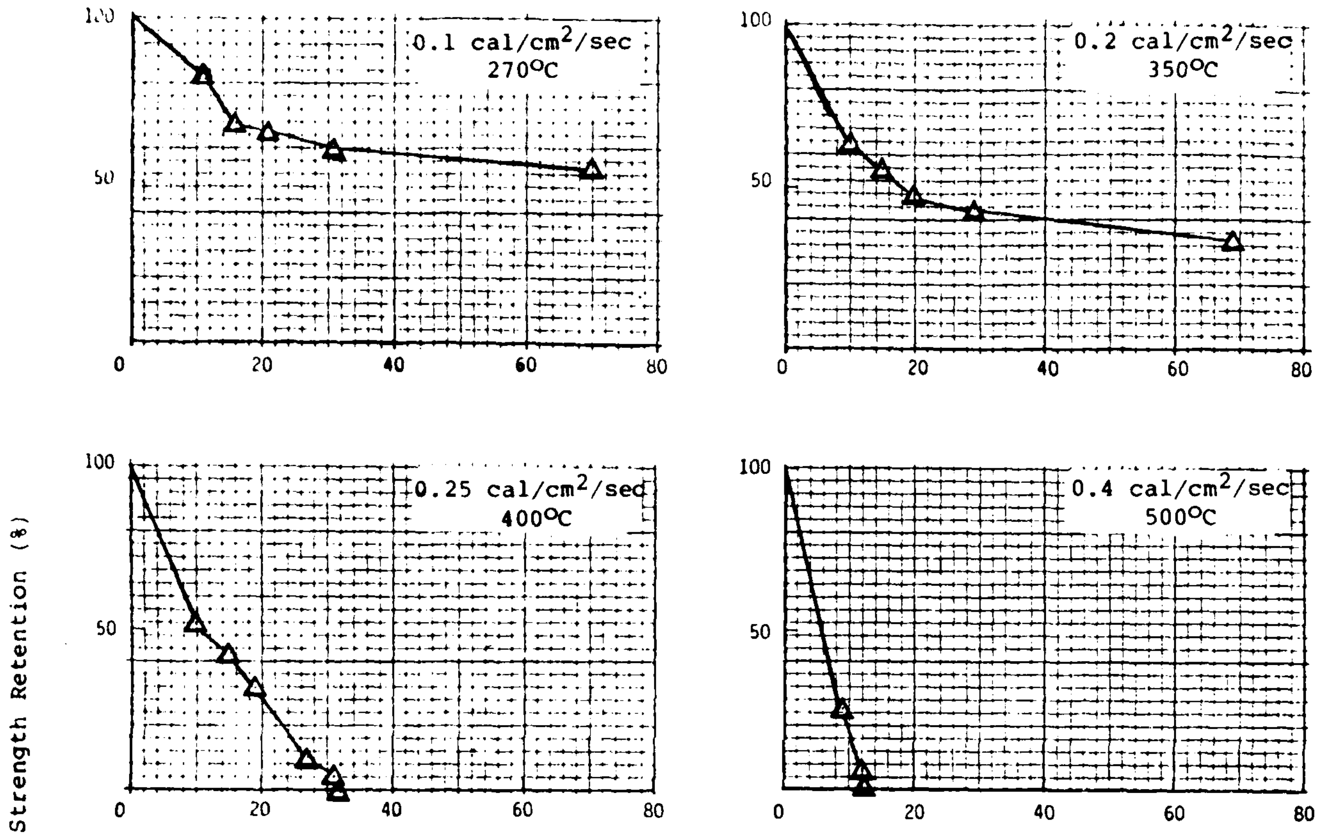
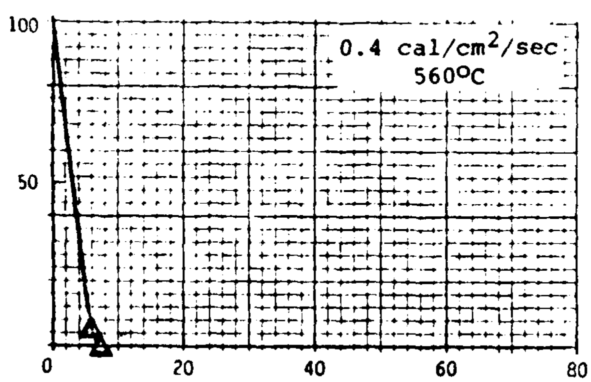


Figure 19b. Modulus of Fabric #2 (55/45 polyester/wool, 6.4 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat





Heat Flux ($cal/cm^2/sec$)	Time to Ignition (sec) Range	Average
0.1	---	---
0.2	---	---
0.25	27-39	32 (glow only)
0.4	14-22	16 (6 of 10 specimens ignited)
0.5	7-8	7
0.6	3-10	6
0.7	4.5-5.5	5

Duration of Exposure (sec)

Figure 20a. Strength Retention of Fabric #3 (100% cotton, 10.3 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat

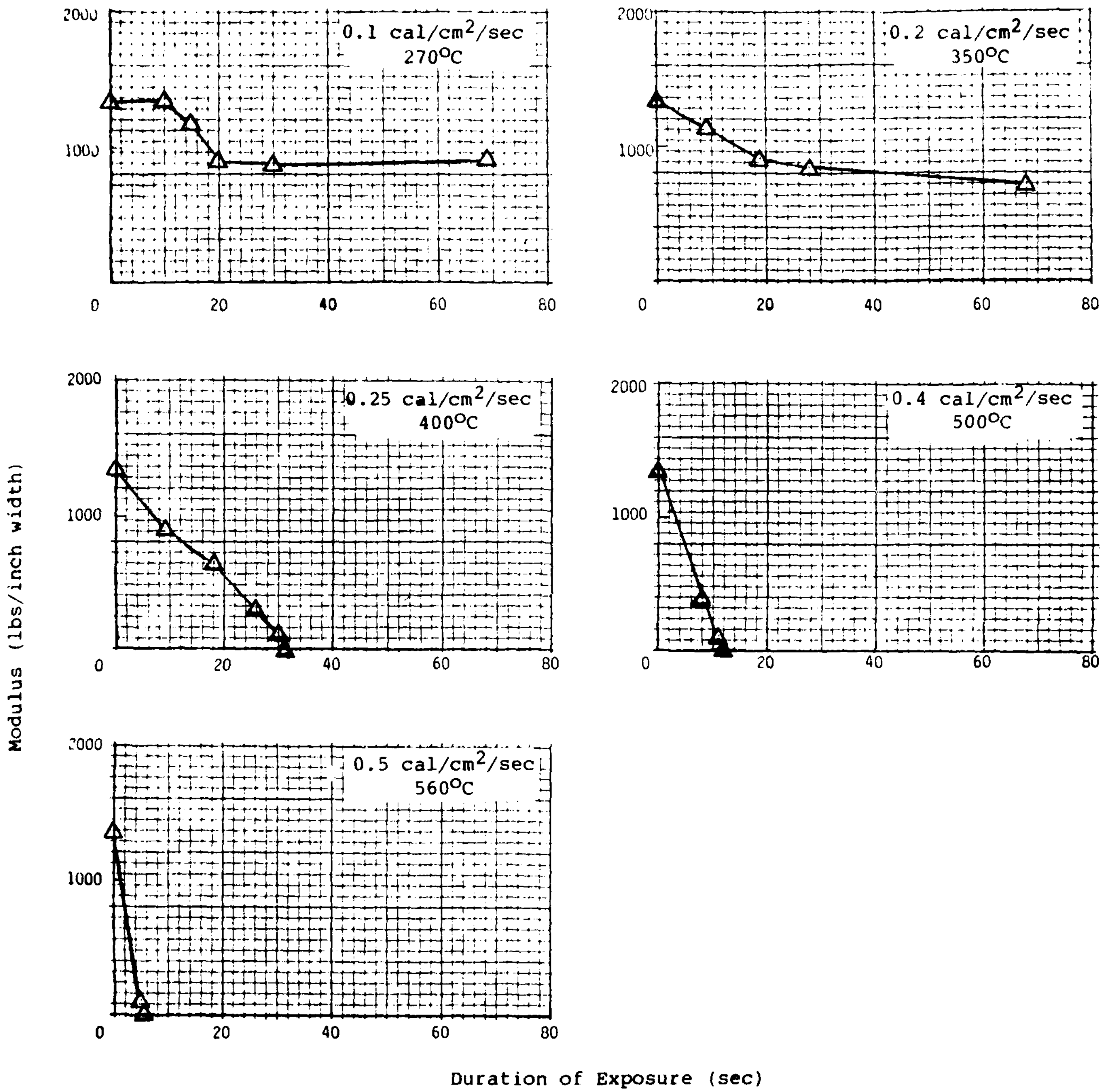
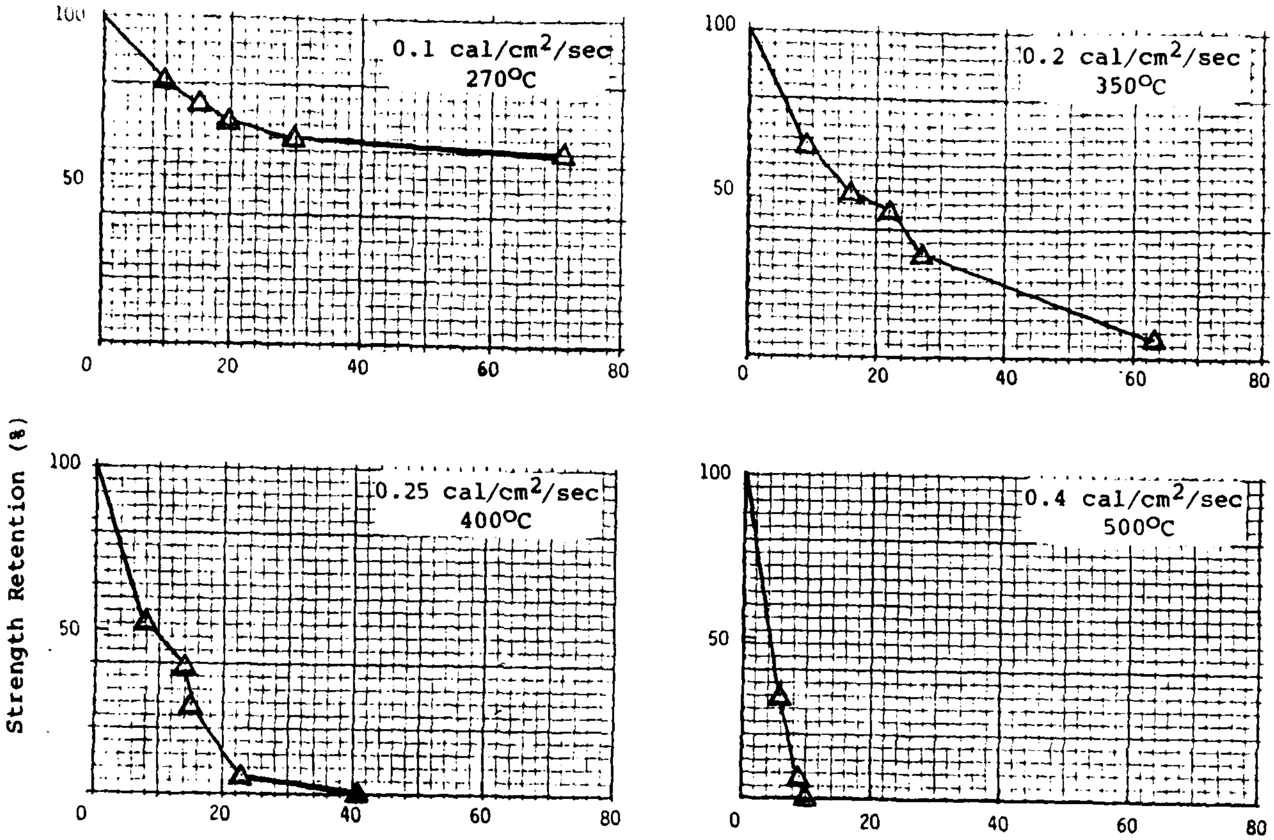
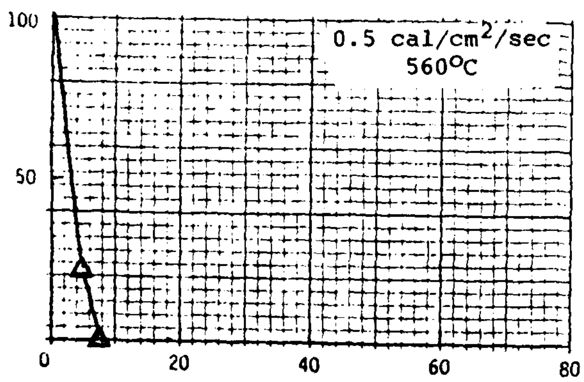


Figure 20b. Modulus of Fabric #3 (100% cotton, 10.3 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat





Heat Flux ($cal/cm^2/sec$)	Time to Ignition (sec) Range	Average
0.1	---	---
0.2	---	---
0.25	---	---
0.4	No ignition, 2 min	
0.5	53-60	56
0.6	7-10	8
0.7	2-5	4

Duration of Exposure (sec)

Figure 21a. Strength Retention of Fabric #4 (50/50 nylon/cotton, 9.3 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat

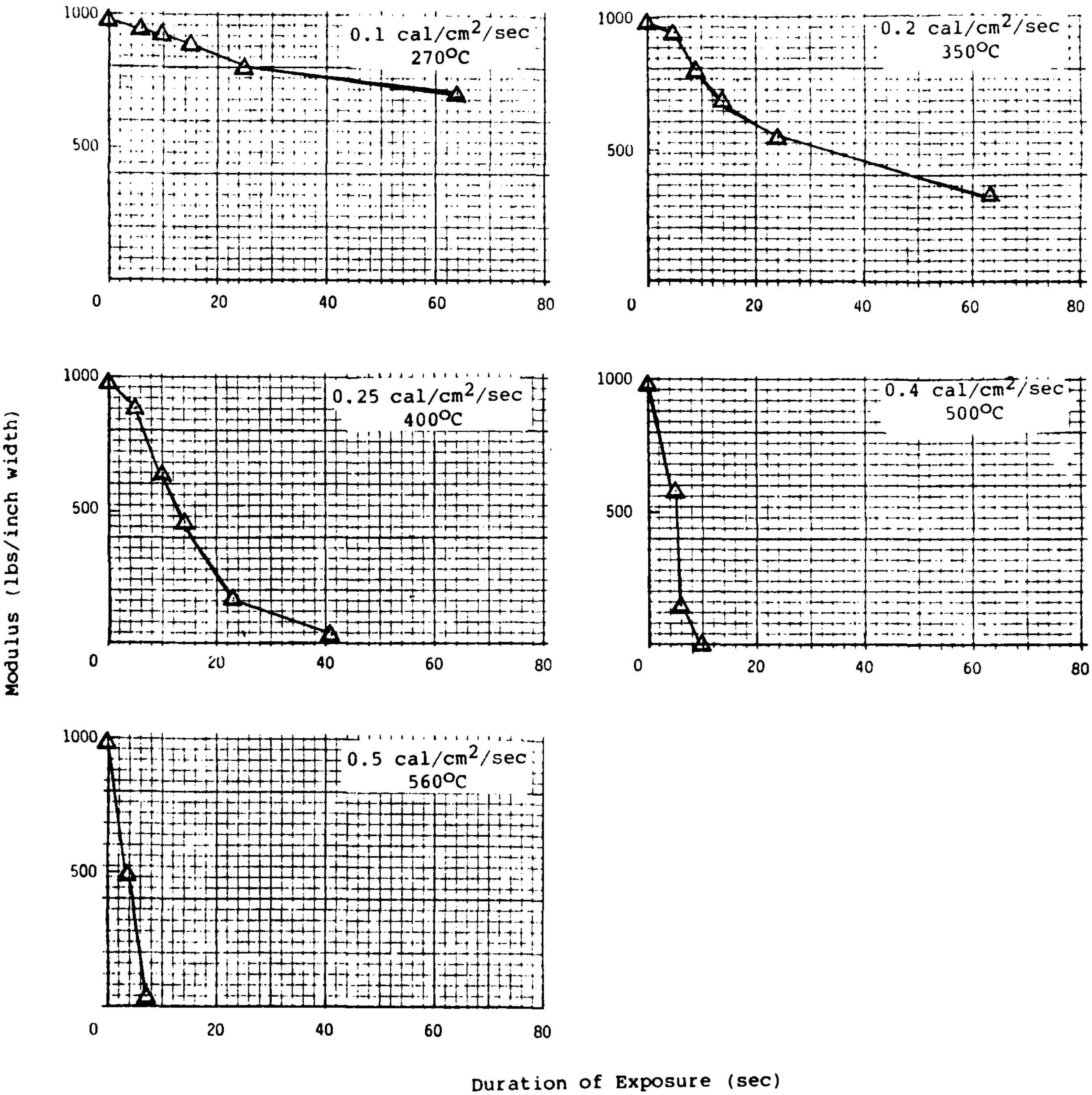
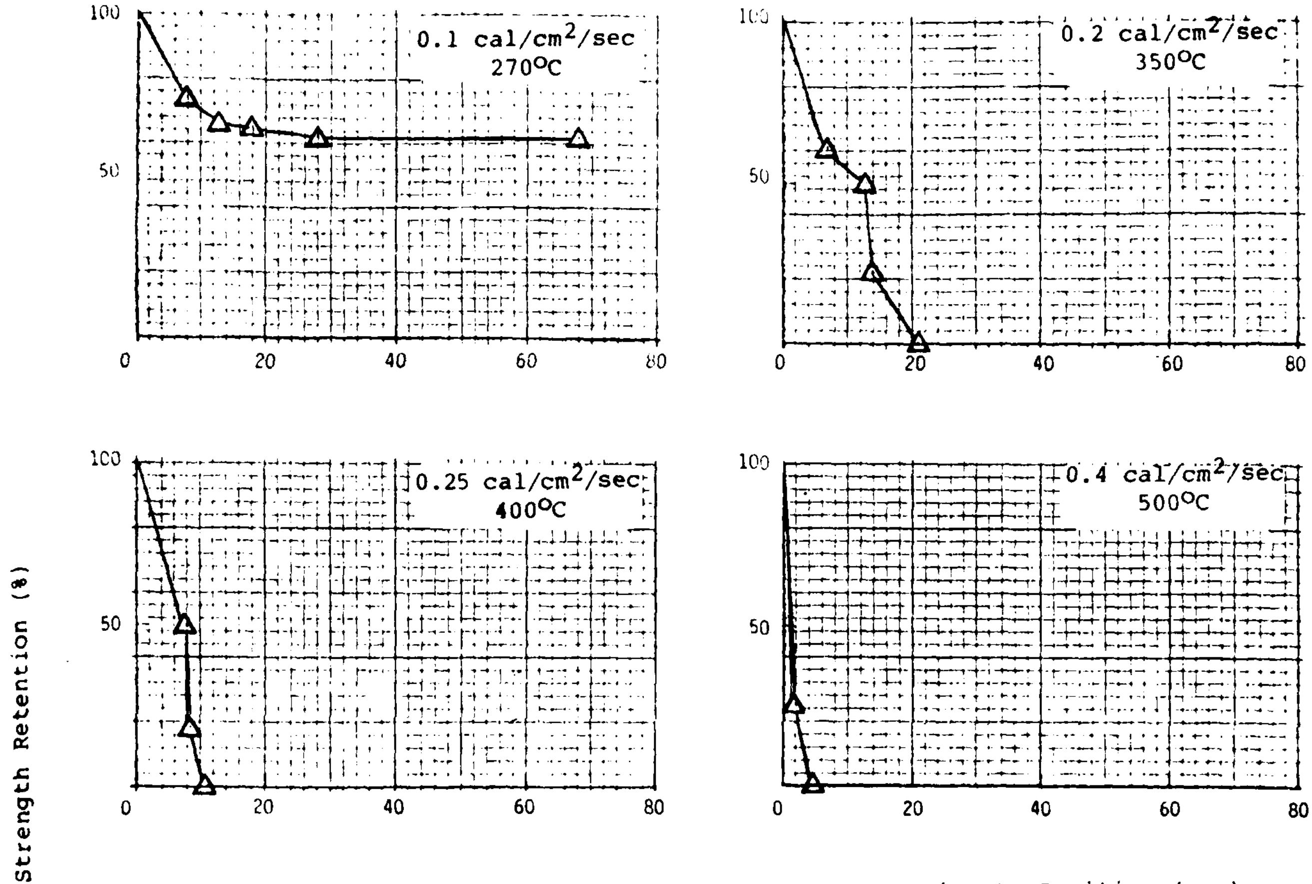
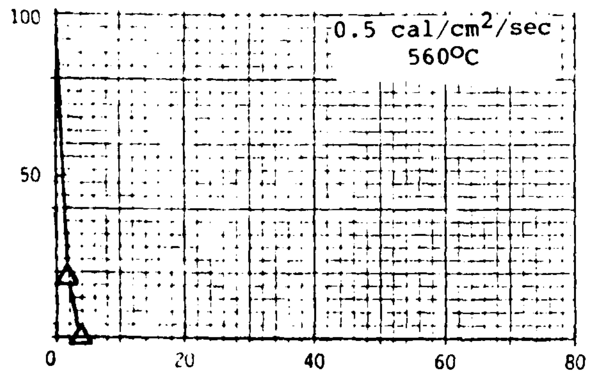


Figure 21b. Modulus of Fabric #4 (50/50 nylon/cotton, 9.3 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat





Heat Flux ($cal/cm^2 sec$)	Time to Ignition (sec) Range	Average
0.1	---	---
0.2	---	---
0.25	---	---
0.4	No ignition, 2 min	
0.5	5-32	14
0.6	4-22	8 (9 of 10 specimens ignited)
0.7	---	

Duration of Exposure (sec)

Figure 22a. Strength Retention of Fabric #6 (65/35 polyester/cotton, 7.0 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat

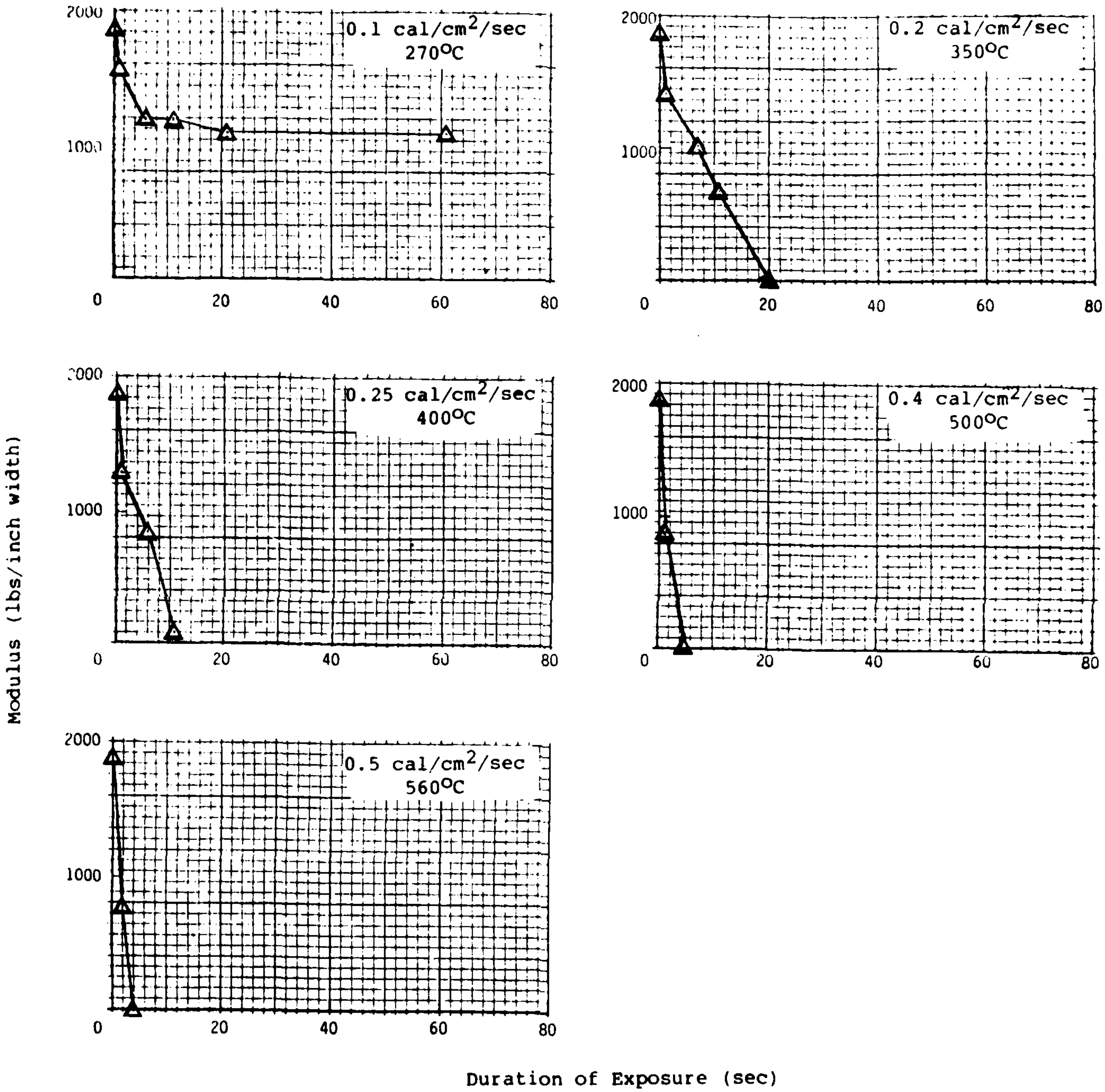
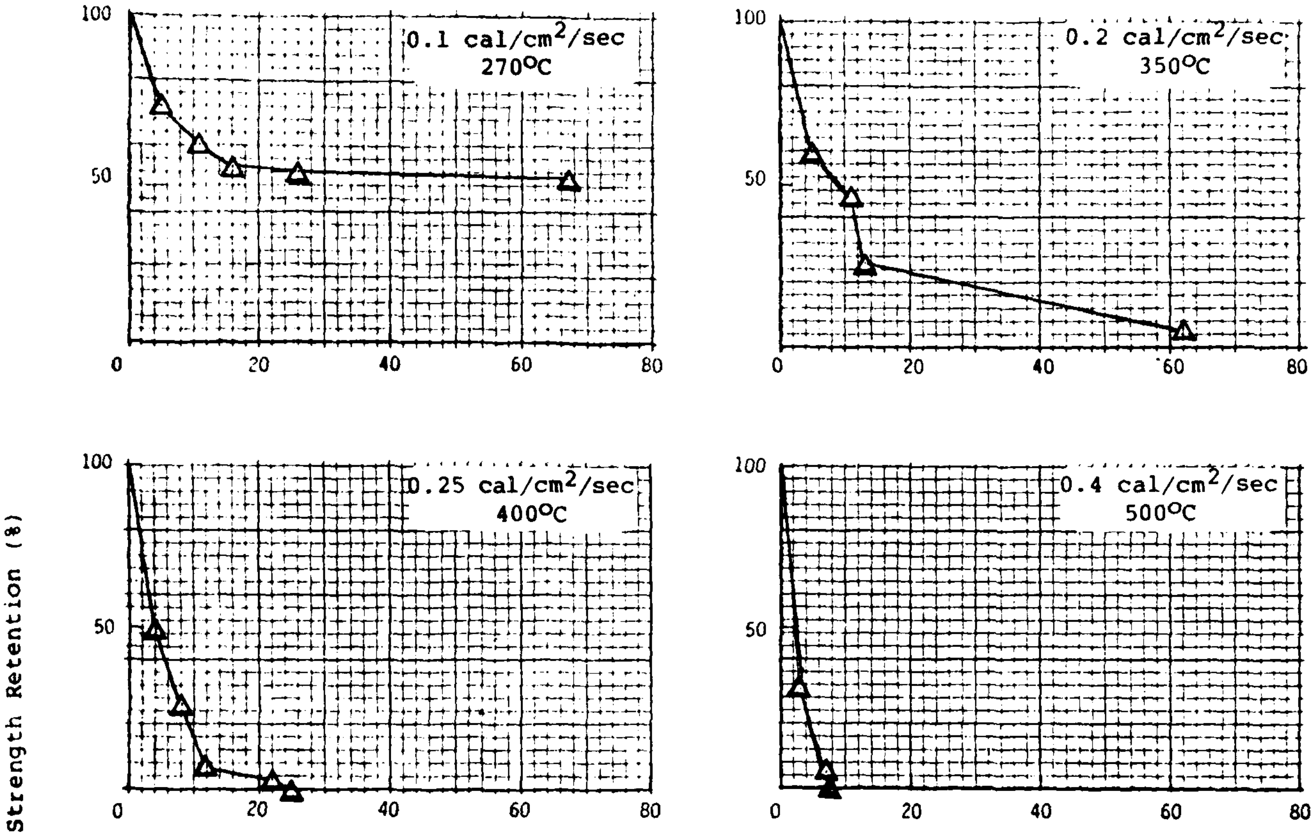
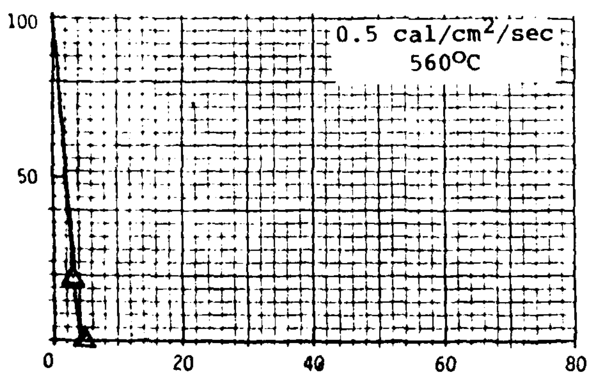


Figure 22b. Modulus of Fabric #6 (65/35 polyester/cotton, 7.0 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat





Heat Flux ($cal/cm^2/sec$)	Time to Ignition (sec) Range	Average
0.1	---	---
0.2	---	---
0.25	---	---
0.4	29-35	31
0.5	---	8
0.6	4-5	4.4
0.7	2-4	3.5

Duration of Exposure (sec)

Figure 23a. Strength Retention of Fabric #7 (50/50 polyester/cotton blend, 6.9 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat

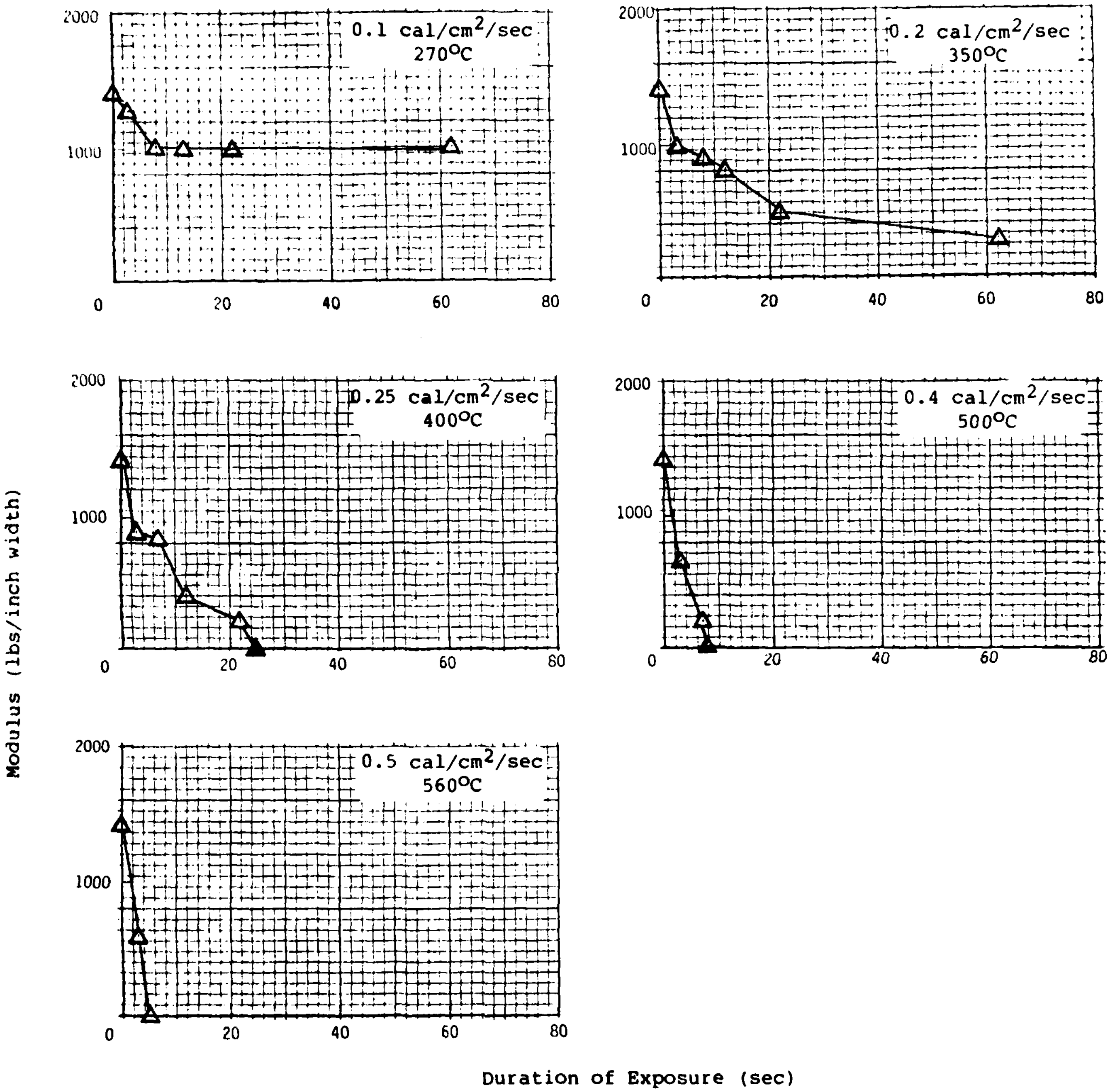
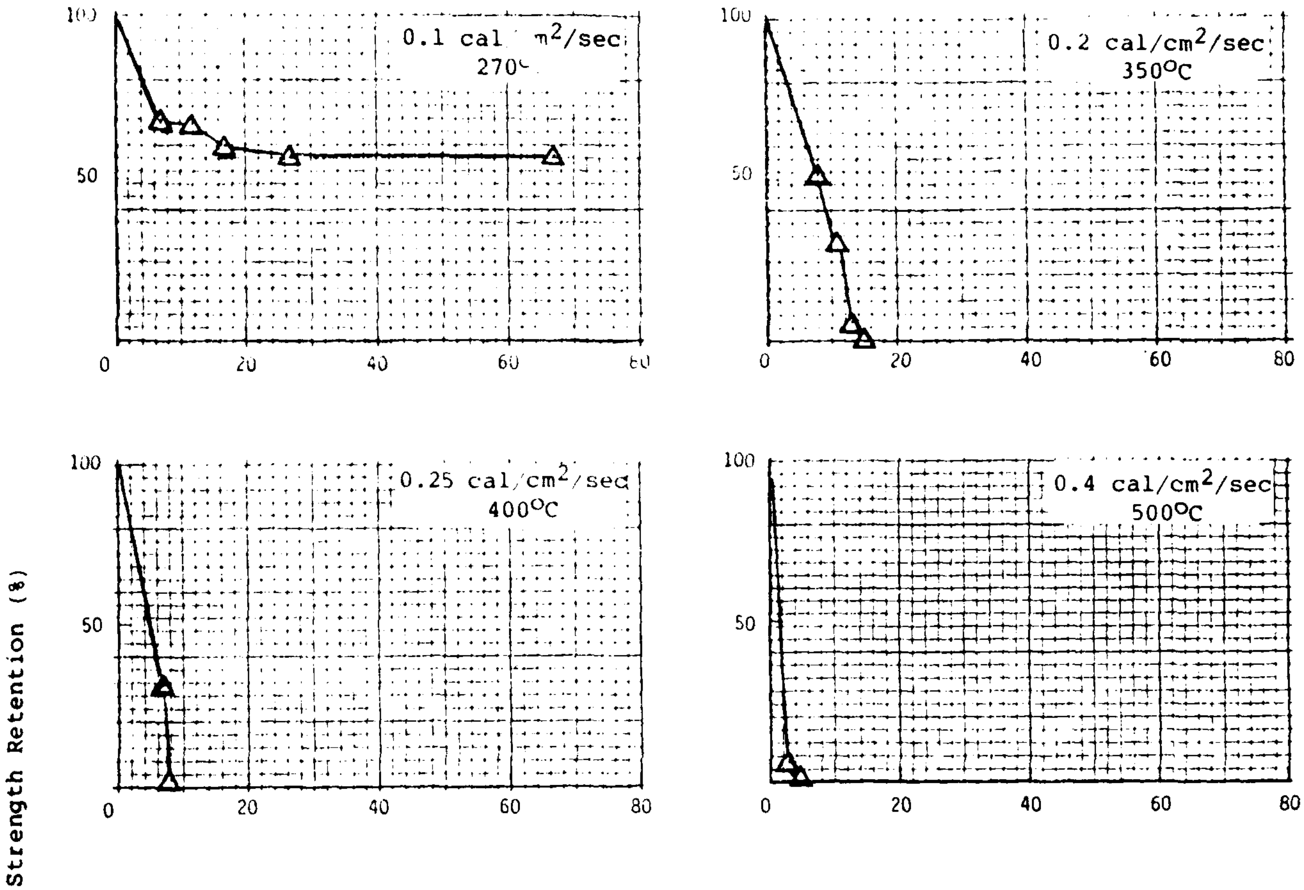
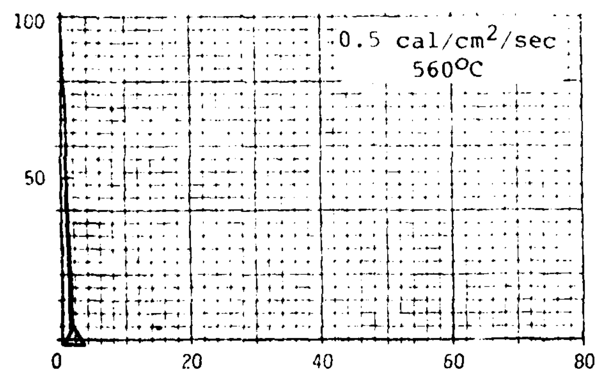


Figure 23b. Modulus of Fabric #7 (50/50 polyester/cotton blend, 6.9 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat





Heat Flux ($cal/cm^2/sec$)	Time to Ignition (sec) Range	Average
0.1	---	---
0.2	---	---
0.25	No ignition, 2 min	
0.4	---	90 (2 of 3 specimens glowed only)
0.5	20-40	32
0.6	11-25	13
0.7	7-18	13

Duration of Exposure (sec)

Figure 24a. Strength Retention of Fabric #8 (75/25 polyester/wool, 6.4 oz/sq yd) During Exposure to Various Levels of Bi-lateral Radiant Heat

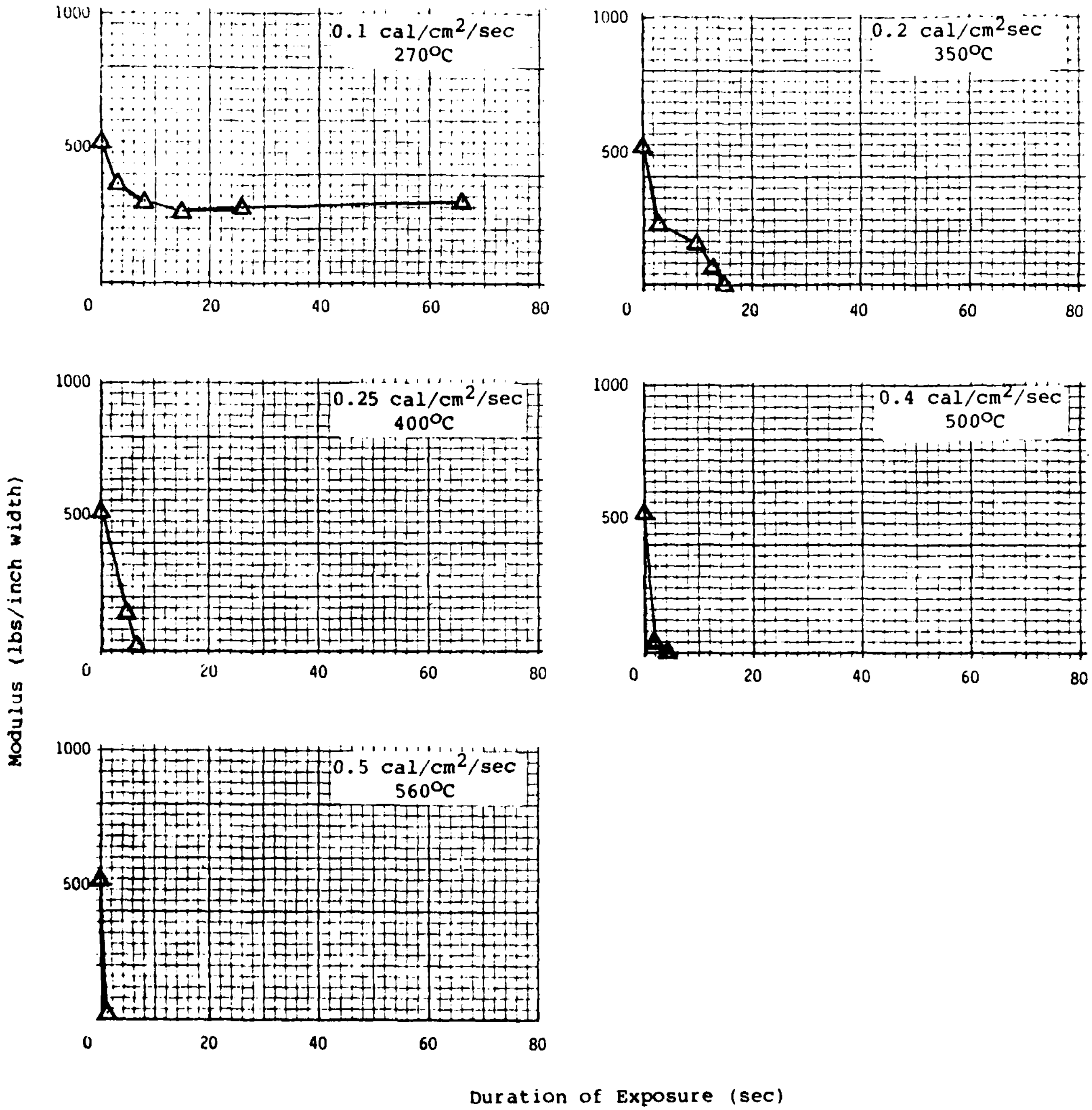
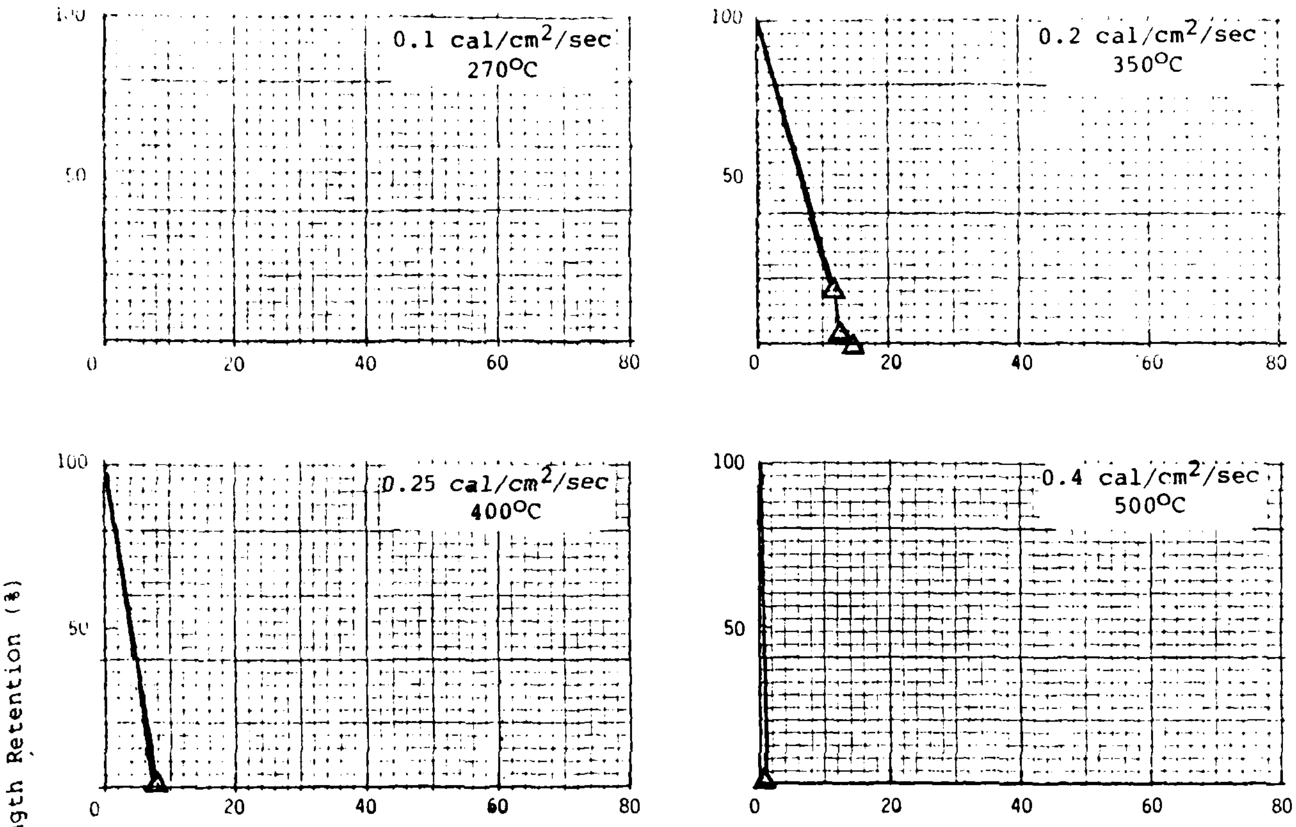


Figure 24b. Modulus of Fabric #8 (75/25 polyester/wool, 6.4 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat



Heat Flux (cal/cm^2/sec)	Time to Ignition (sec) Range	Average
0.1	---	---
0.2	melted, 18-20 seconds	
0.25	melted, 10 seconds	
0.4	melted, 5 seconds	
0.5	melted, 3 seconds	
0.6	melted, 3 seconds	
0.7	melted, 3 seconds	

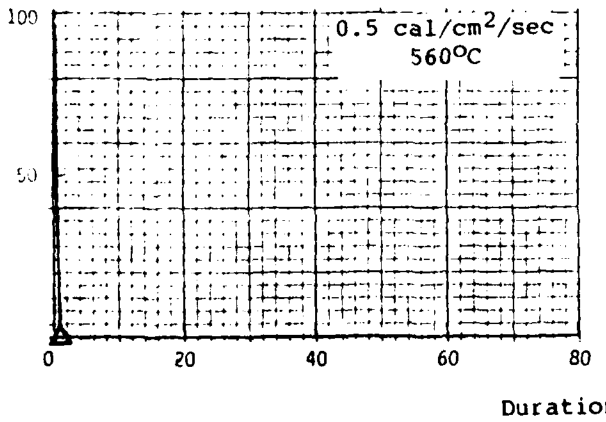
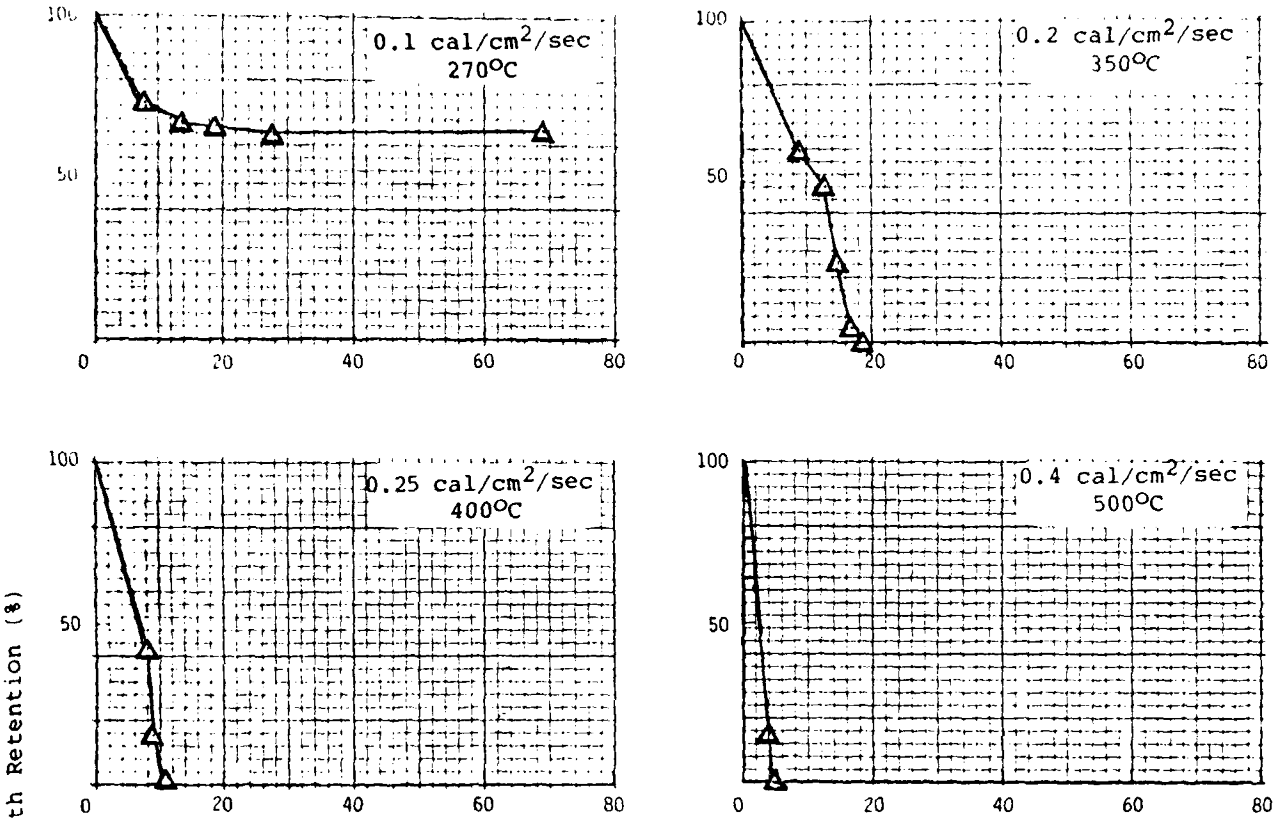
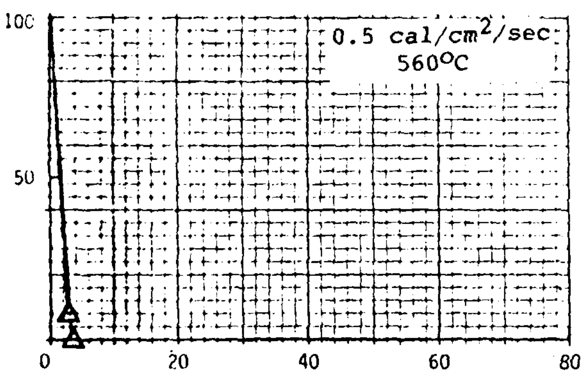


Figure 25a. Strength Retention of Fabric #9 (100% polyester, 6.0 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat





Heat Flux ($cal/cm^2/sec$)	Time to Ignition (sec) Range	Average
0.1	---	---
0.2	---	---
0.25	No ignition, 2 min	
0.4	72-105	84 (glow only)
0.5	5-6	5
0.6	---	4
0.7	---	3

Duration of Exposure (sec)

Figure 26a. Strength Retention of Fabric #10 (65/35 polyester/rayon, 5.9 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat

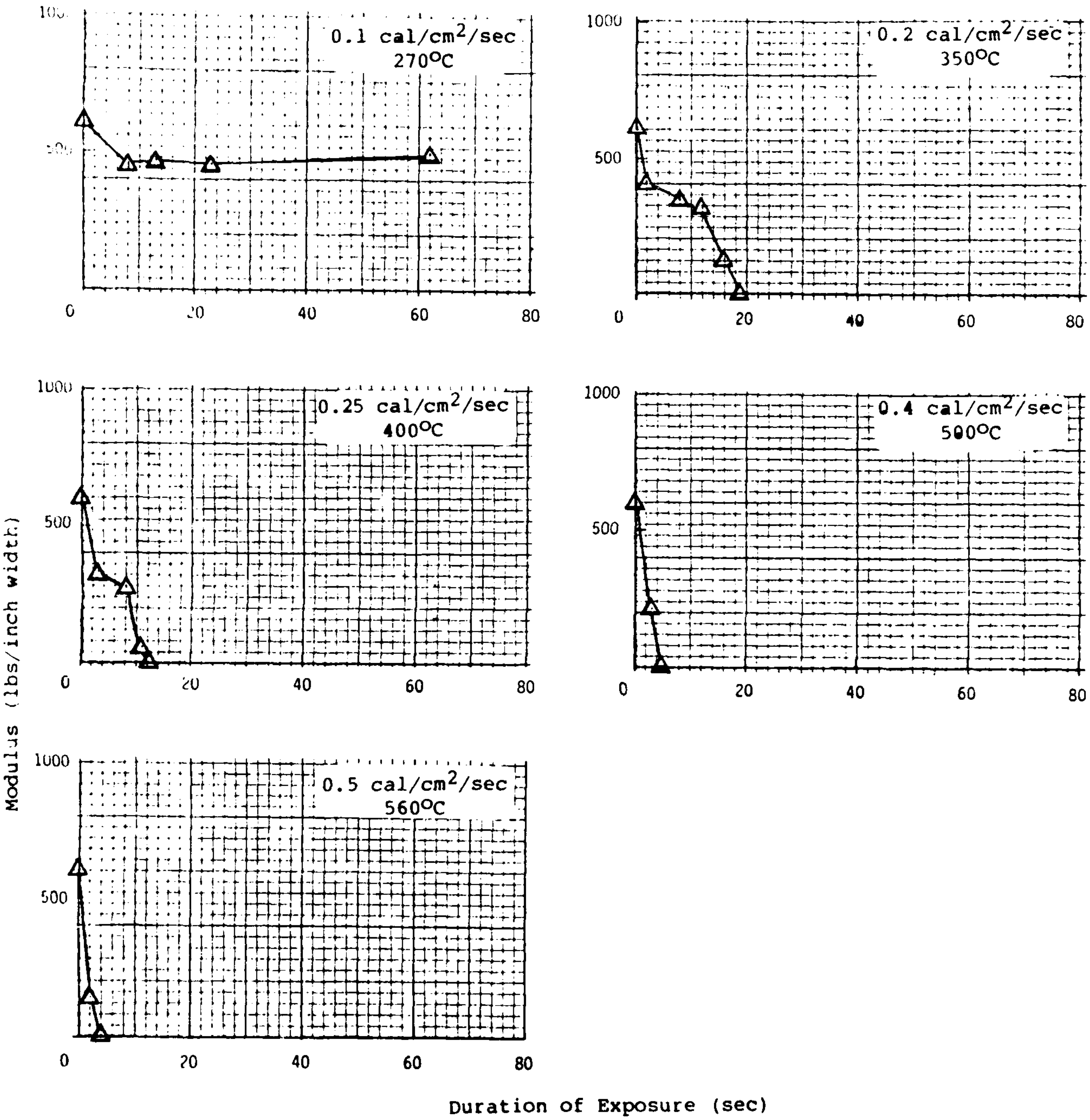
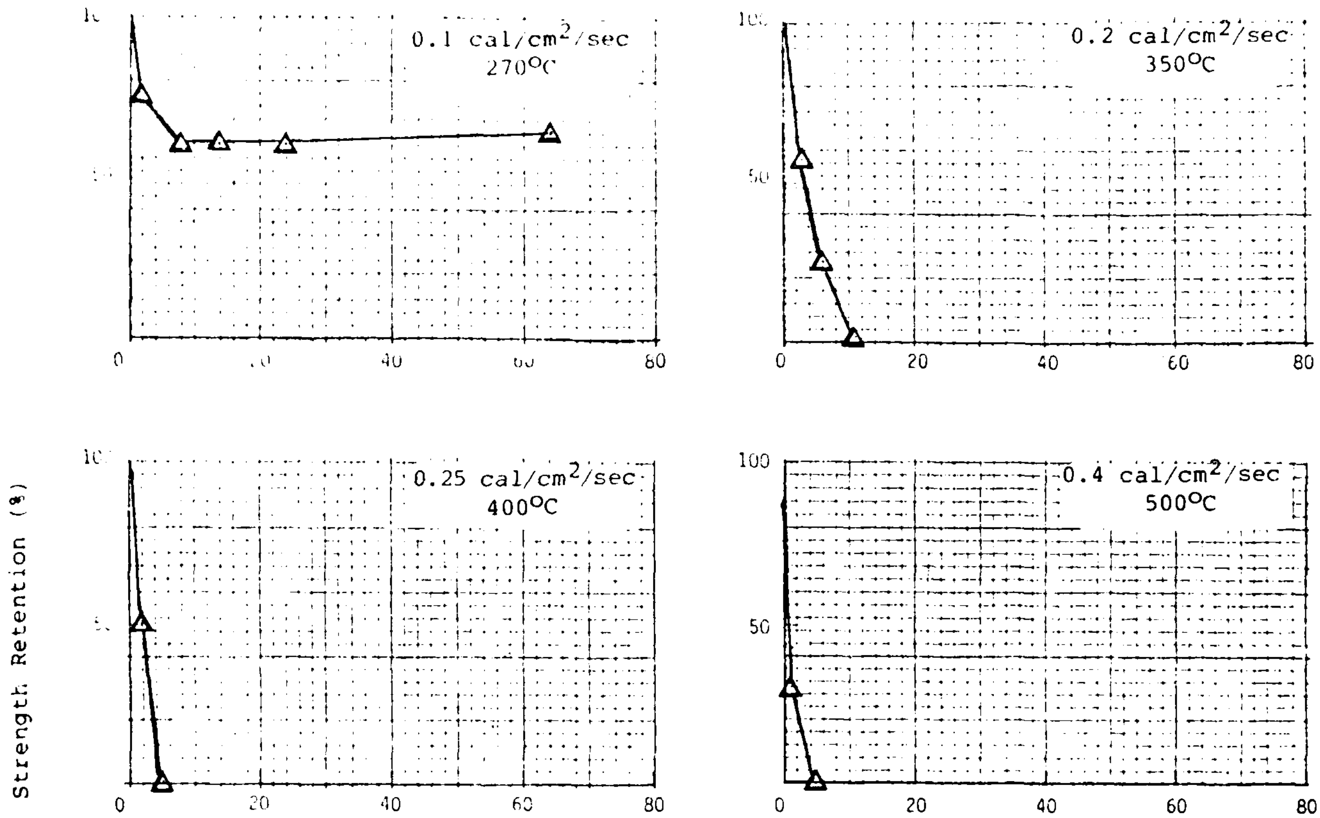
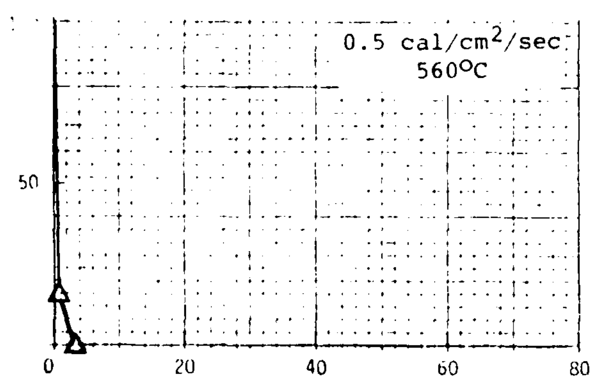


Figure 26b. Modulus of Fabric #10 (65/35 polyester/rayon, 5.9 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat





Heat Flux (cal/cm^2/sec)	Time to Ignition (sec) Range	Average
0.1	---	---
0.2	---	---
0.25	---	---
0.4	No ignition, 2 min	
0.5	4-5	5
0.6	3-4	3
0.7	---	2

Duration of Exposure (sec)

Figure 27a. Strength Retention of Fabric #11 (50/50 polyester/cotton, 3.5 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat

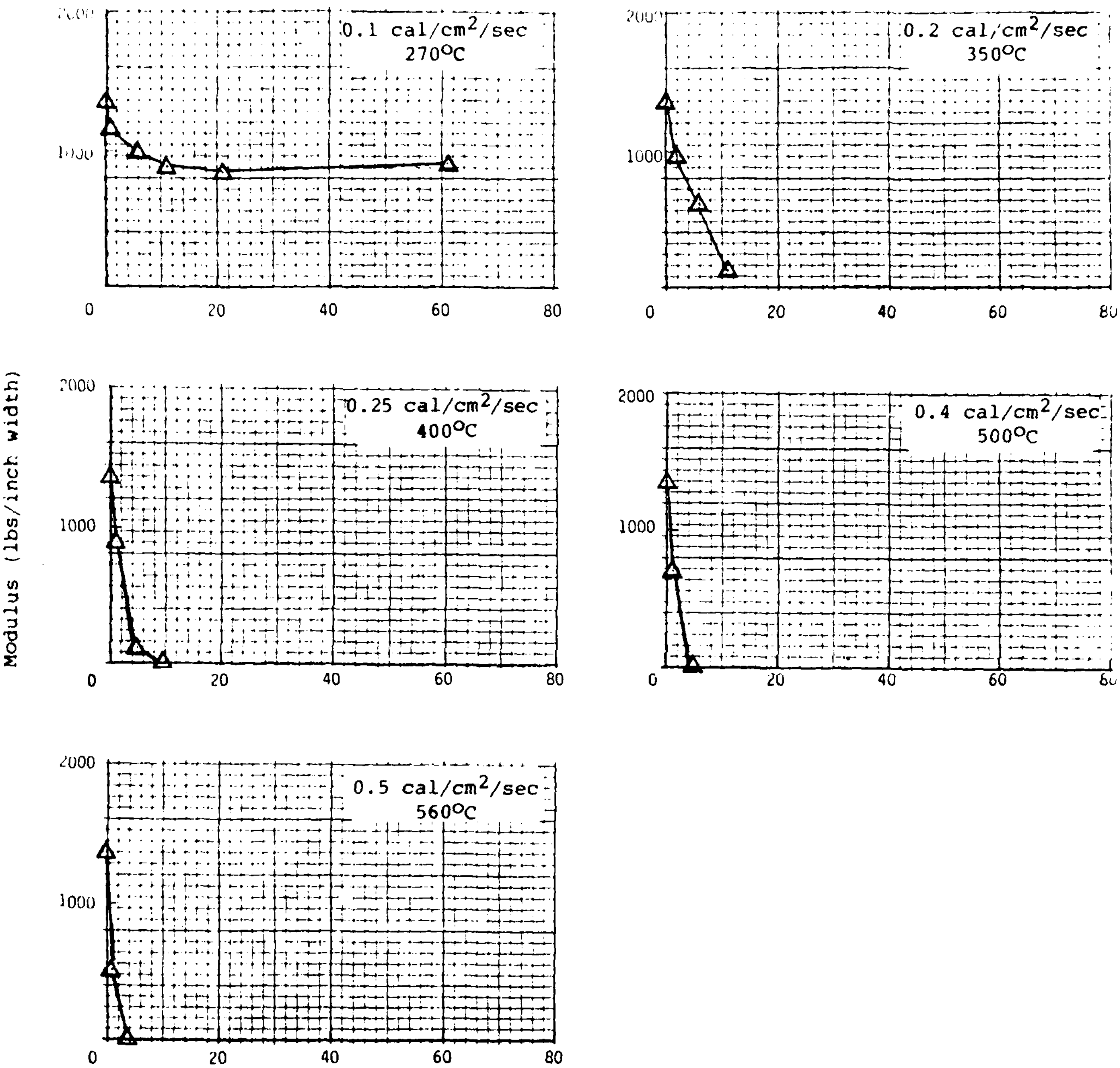
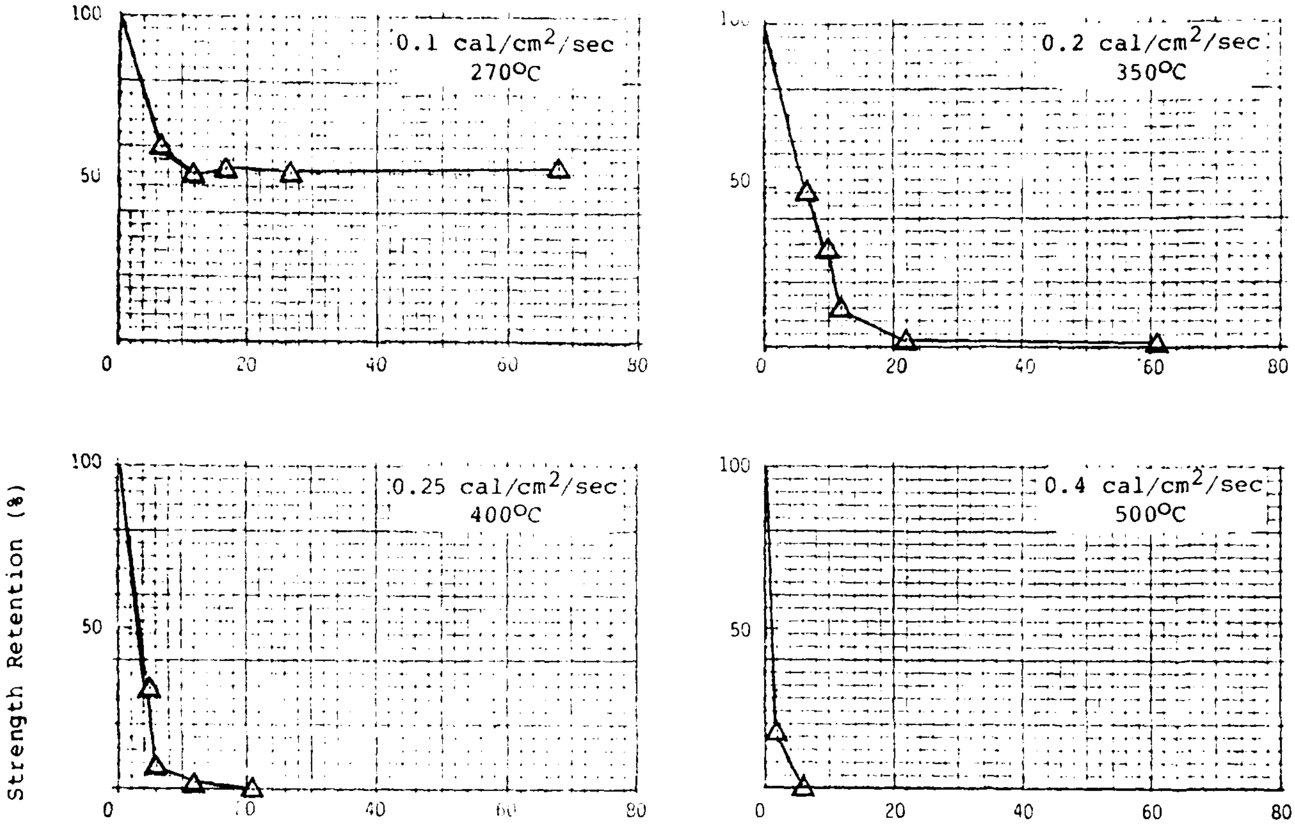
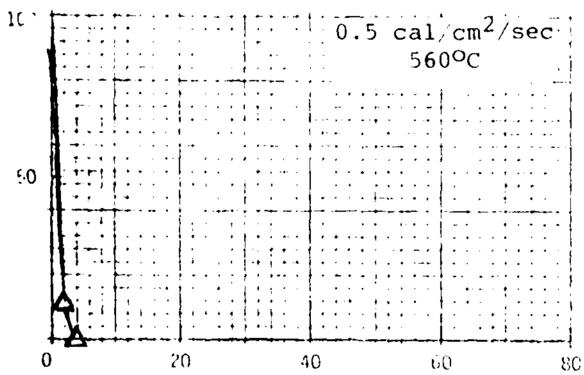


Figure 27b. Modulus of Fabric #11 (50/50 polyester/cotton, 3.5 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat





Heat Flux (cal/cm^2/sec)	Time to Ignition (sec) Range	Average
0.1	---	---
0.2	---	---
0.25	No ignition, 2 min	
0.4	43-102	60 (6 of 7 specimens ignited)
0.5	7-8	7
0.6	---	5
0.7	---	3

Duration of Exposure (sec)

Figure 28a. Strength Retention of Fabric #12 (65/35 polyester/cotton, 4.8 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat

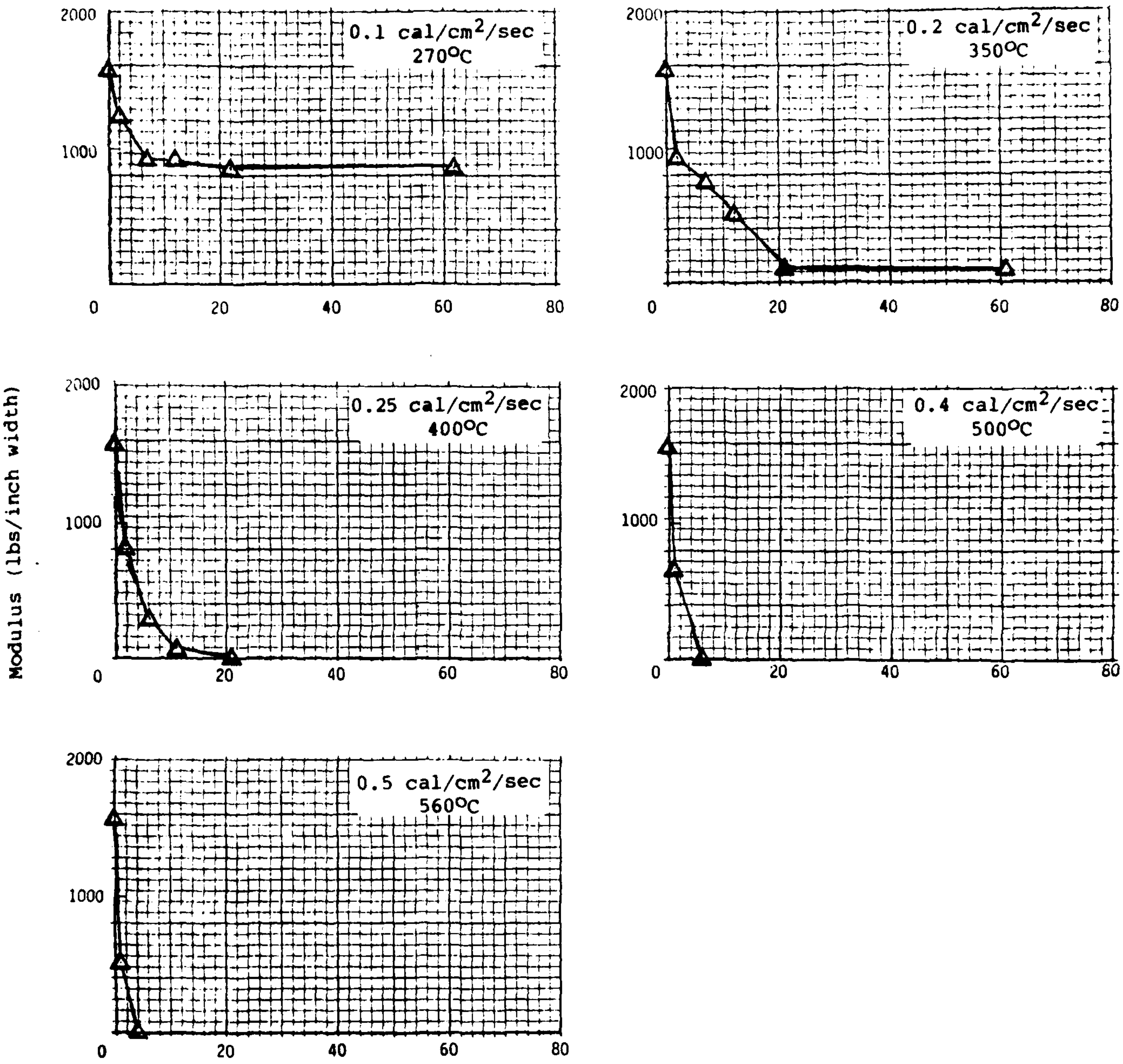
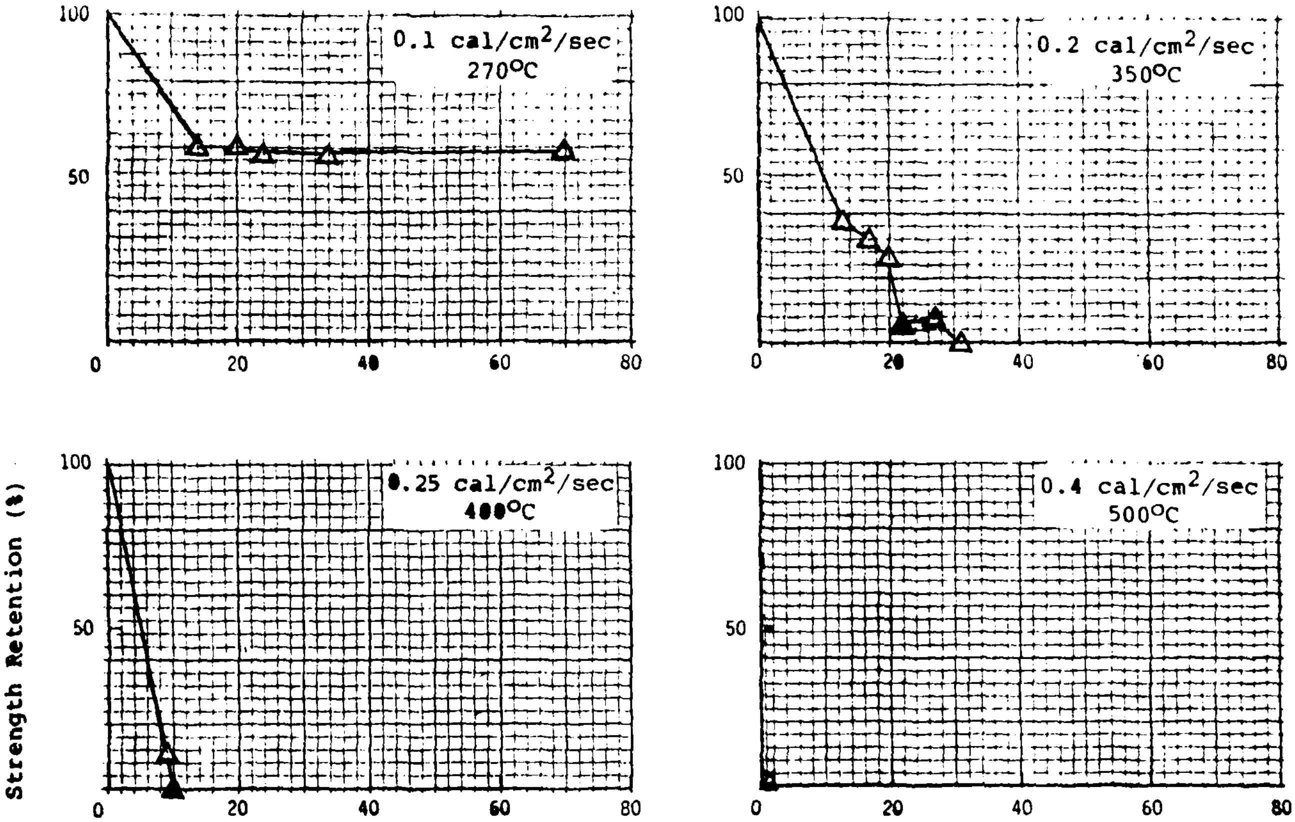
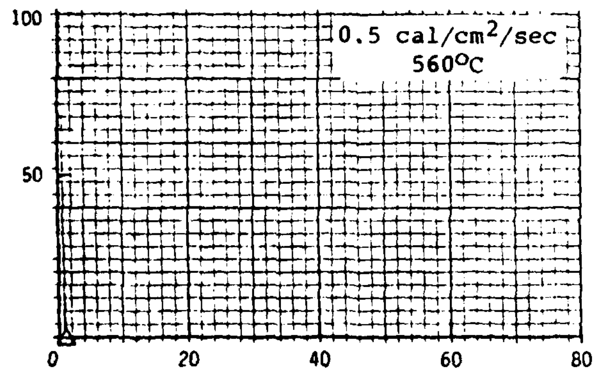


Figure 28b. Modulus of Fabric #12 (65/35 polyester/cotton, 4.8 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat





Heat Flux ($cal/cm^2/sec$)	Time to Ignition (sec) Range	Average
0.1	---	---
0.2	melted, 10-19 seconds	
0.25	melted, 9-12 seconds	
0.4	melted immediately	
0.5	melted immediately	
0.6	melted immediately	
0.7	melted immediately	

Duration of Exposure (sec)

Figure 29a. Strength Retention of Fabric #13 (100% polyester, 6.0 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat

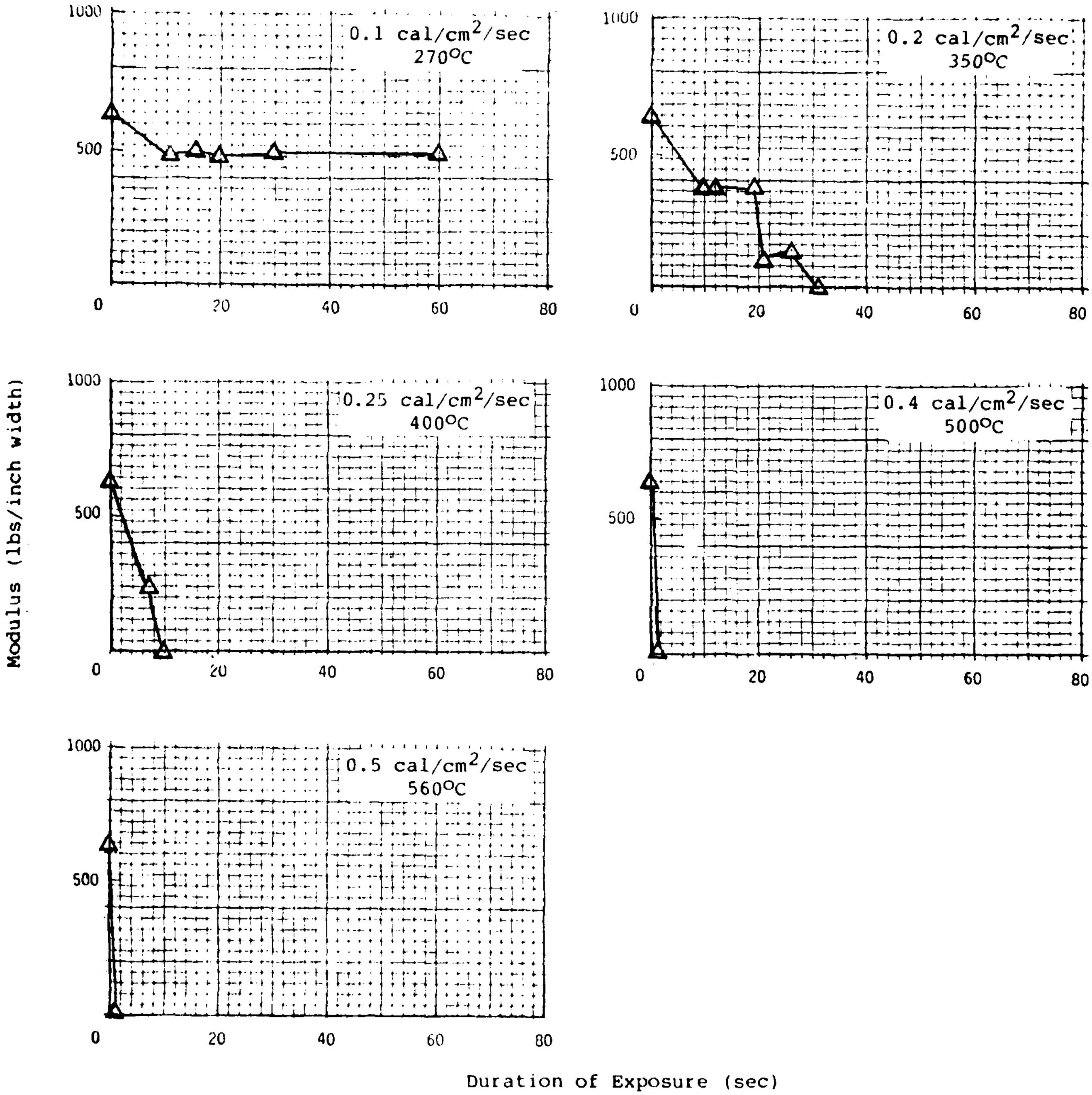
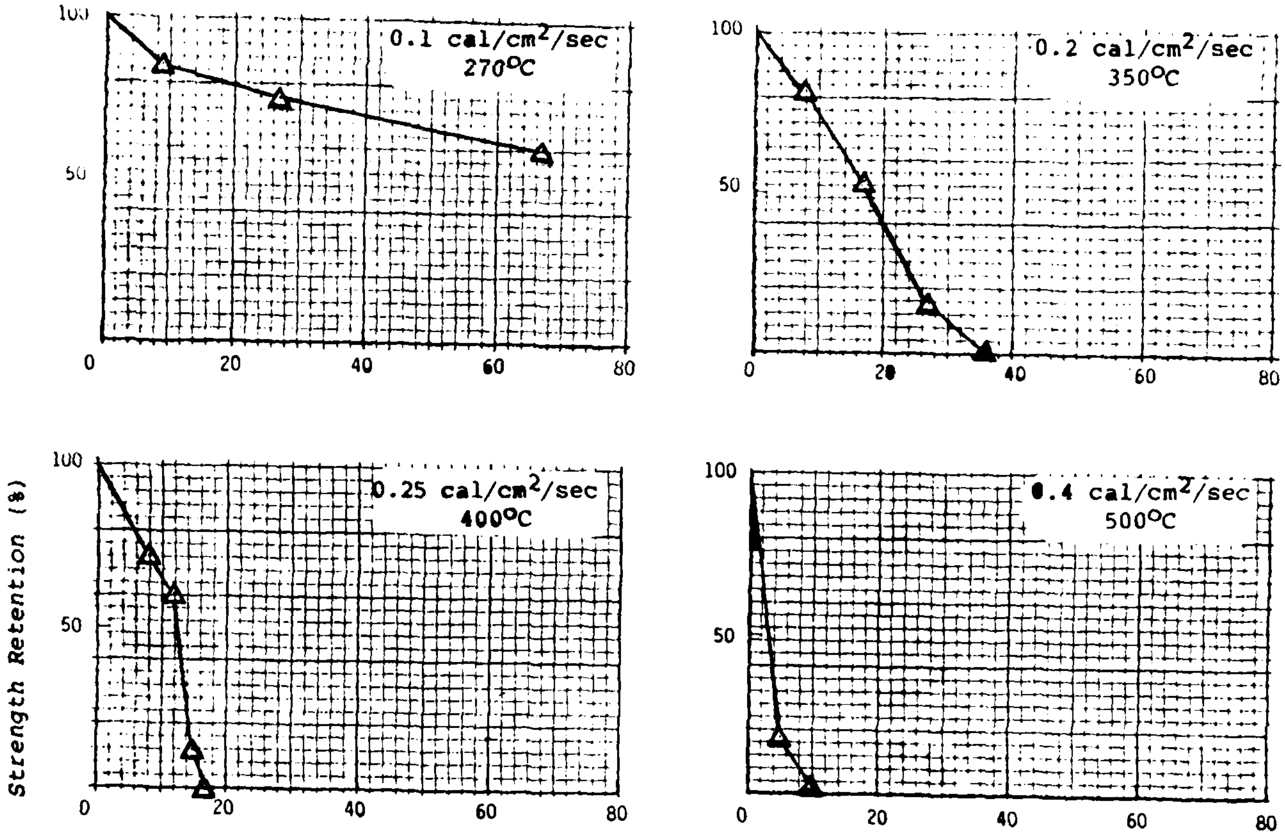
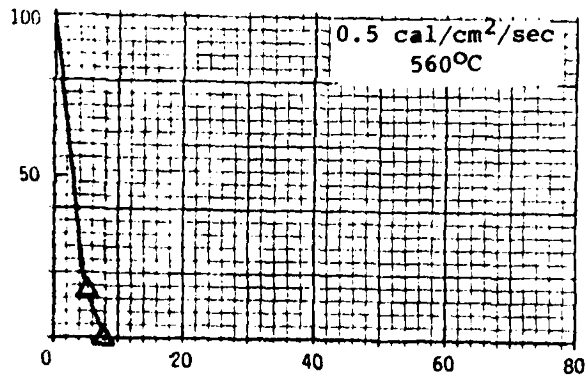


Figure 29b. Modulus of Fabric #13 (100% polyester, 6.0 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat





Heat Flux ($cal/cm^2/sec$)	Time to Ignition (sec) Range	Average
0.1	---	---
0.2	---	---
0.25	No ignition, 2 min	
0.4	53-70	61 (glow only)
0.5	25-39	35
0.6	21-32	27 (4 of 5 specimens ignited)
0.7	16-21	18

Duration of Exposure (sec)

Figure 30a. Strength Retention of Fabric #14 (100% wool, 8.4 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat

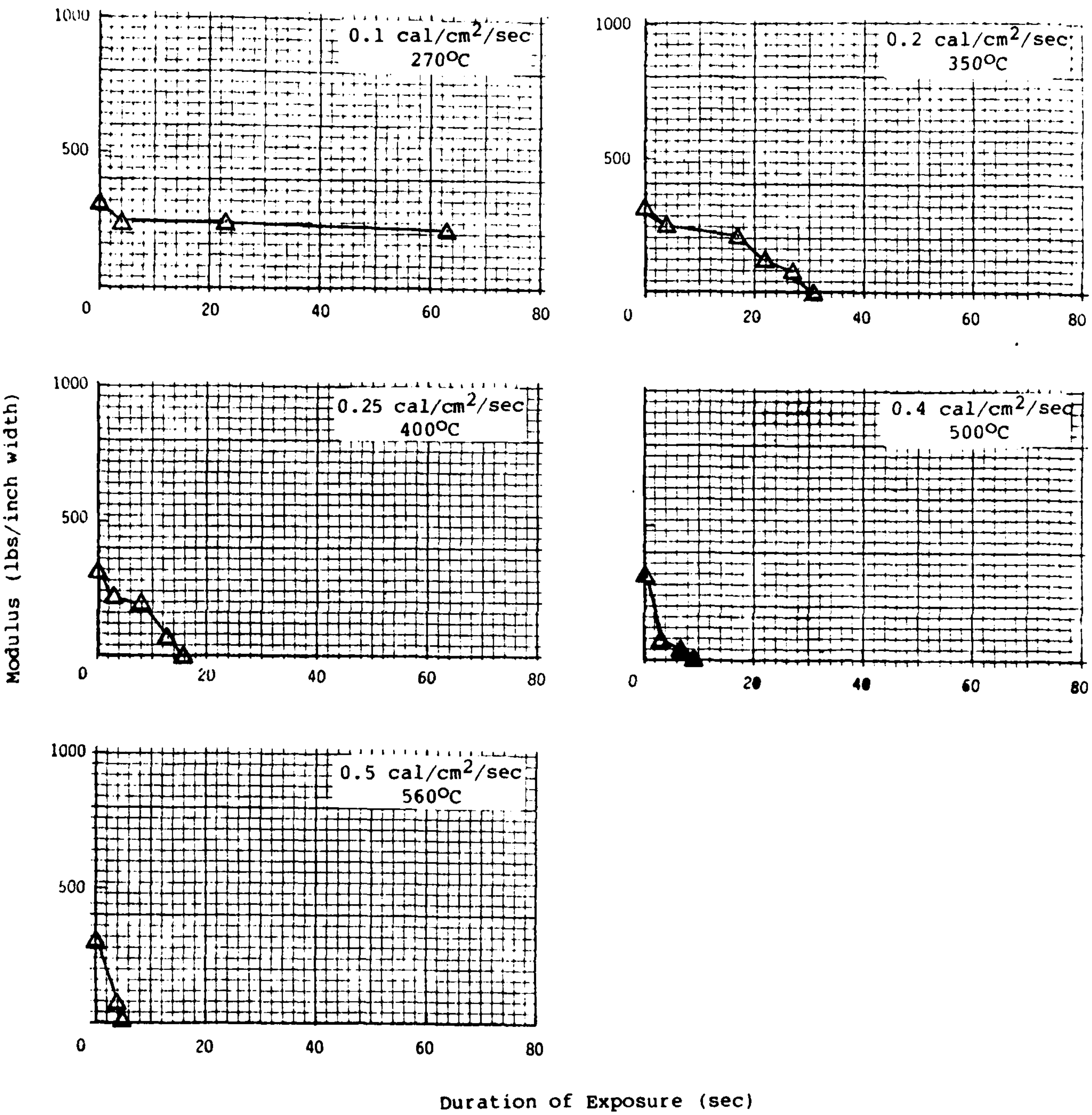
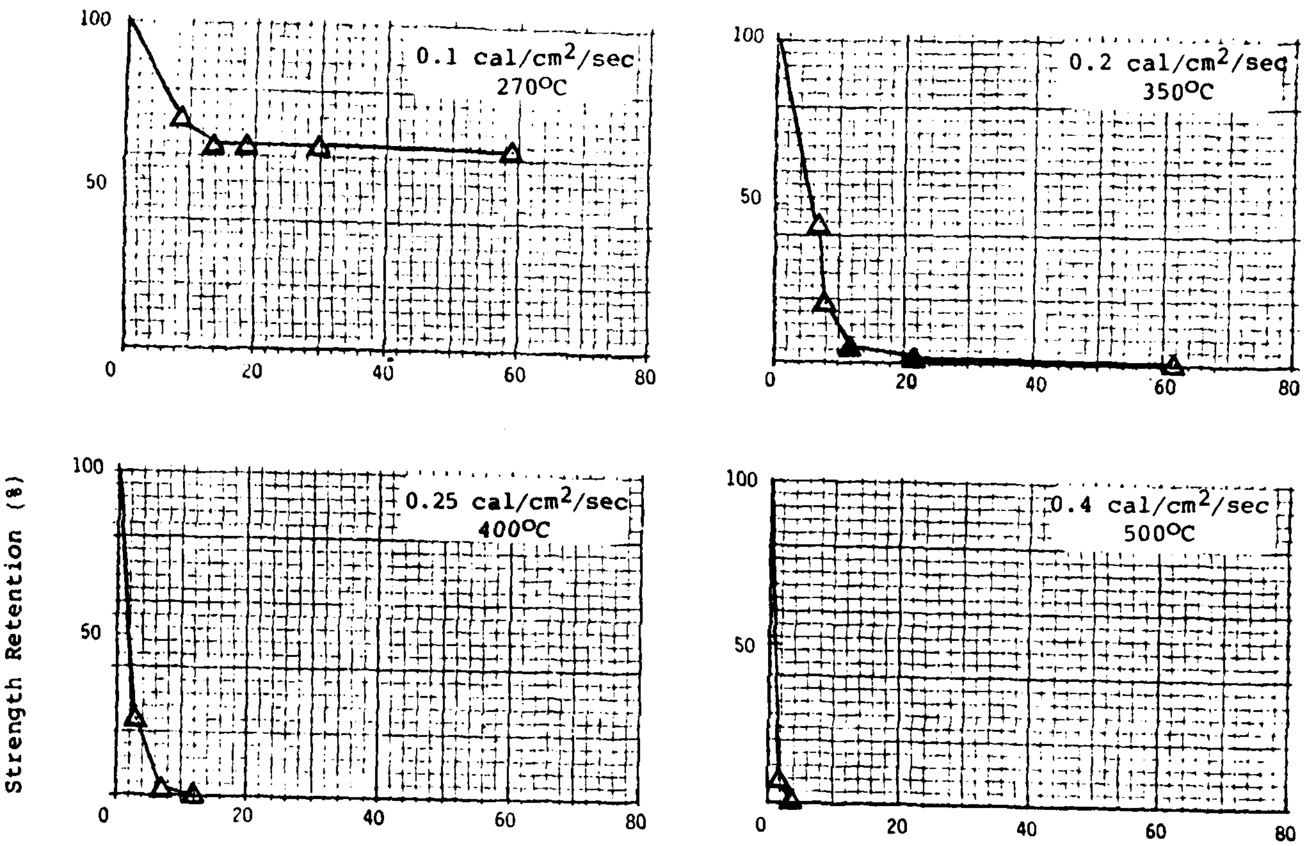
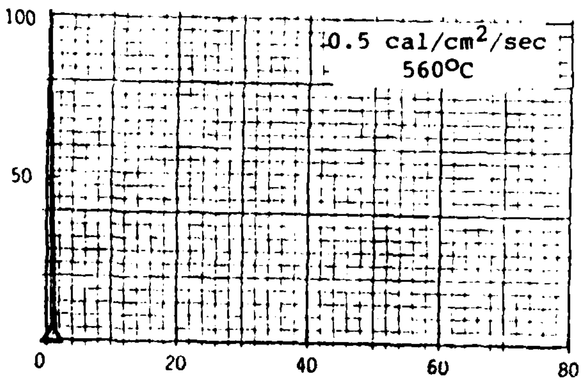


Figure 30b. Modulus of Fabric #14 (100% wool, 8.4 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat





Heat Flux ($cal/cm^2/sec$)	Time to Ignition (sec) Range	Average
0.1	---	---
0.2	---	---
0.25	---	---
0.4	No ignition, 2 min	
0.5	5-20	8
0.6	4-5	4
0.7	---	3

Duration of Exposure (sec)

Figure 31a. Strength Retention of Fabric #15 (65/35 polyester/cotton, 4.4 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat

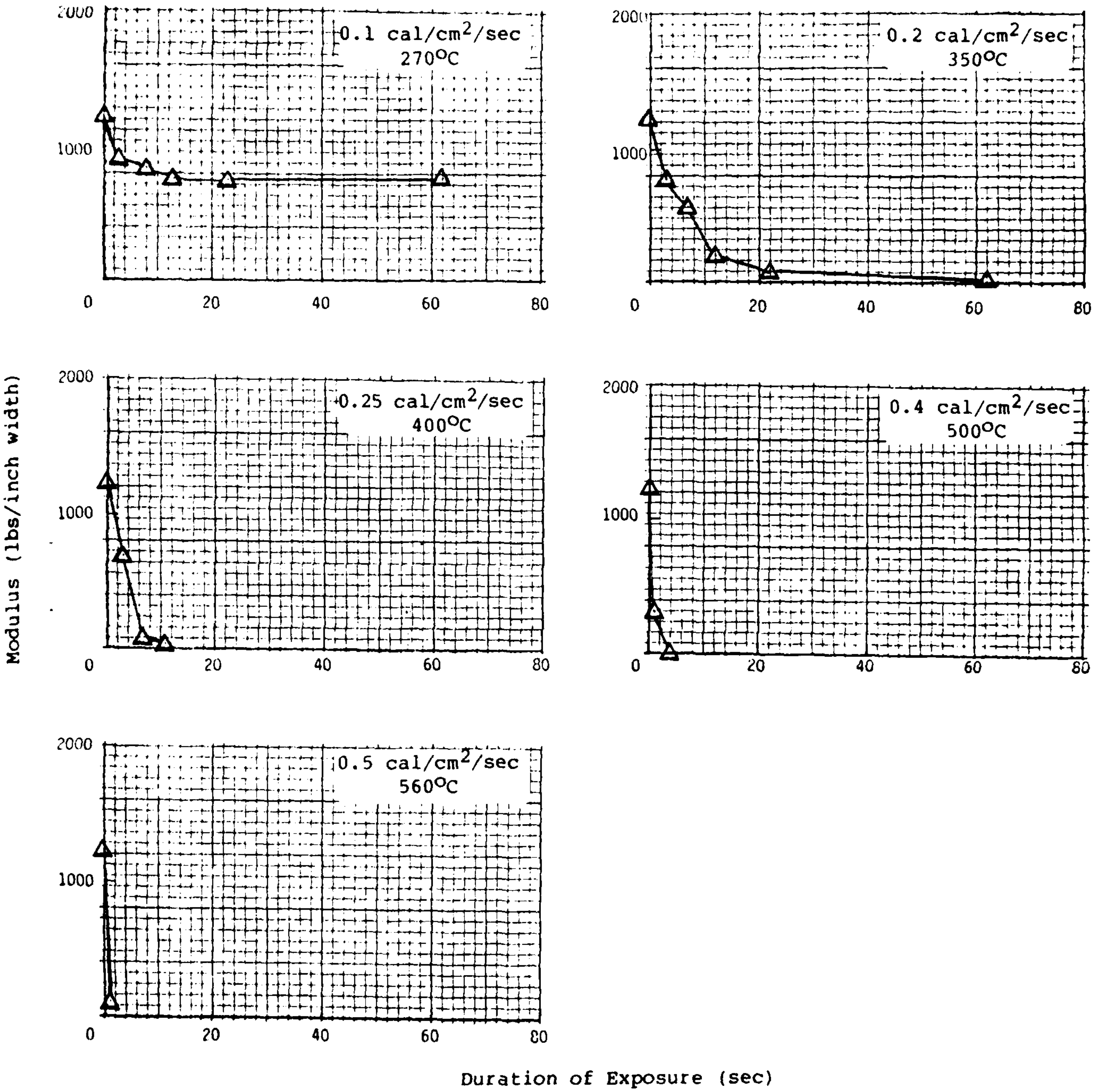
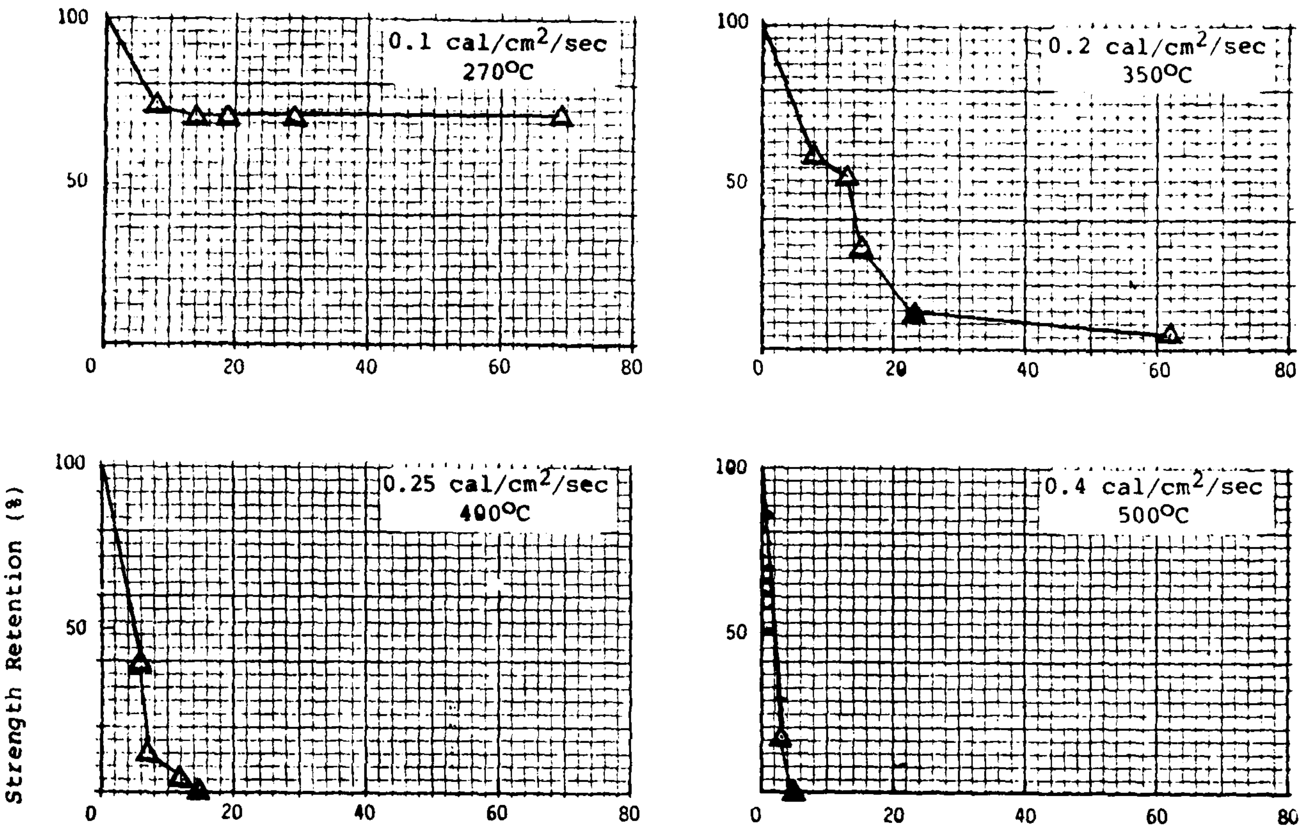


Figure 31b. Modulus of Fabric #15 (65/35 polyester/cotton, 4.4 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat



Heat Flux (cal/cm^2/sec)	Time to Ignition (sec) Range	Average
0.1	---	---
0.2	---	---
0.25	---	---
0.4	---	---
0.5	5-12	7
0.6	2-6	4
0.7	1-3	2

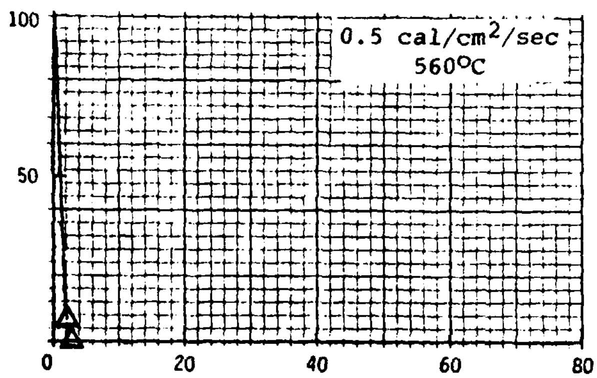


Figure 32a. Strength Retention of Fabric #16 (65/35 polyester/cotton blend, 5.8 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat

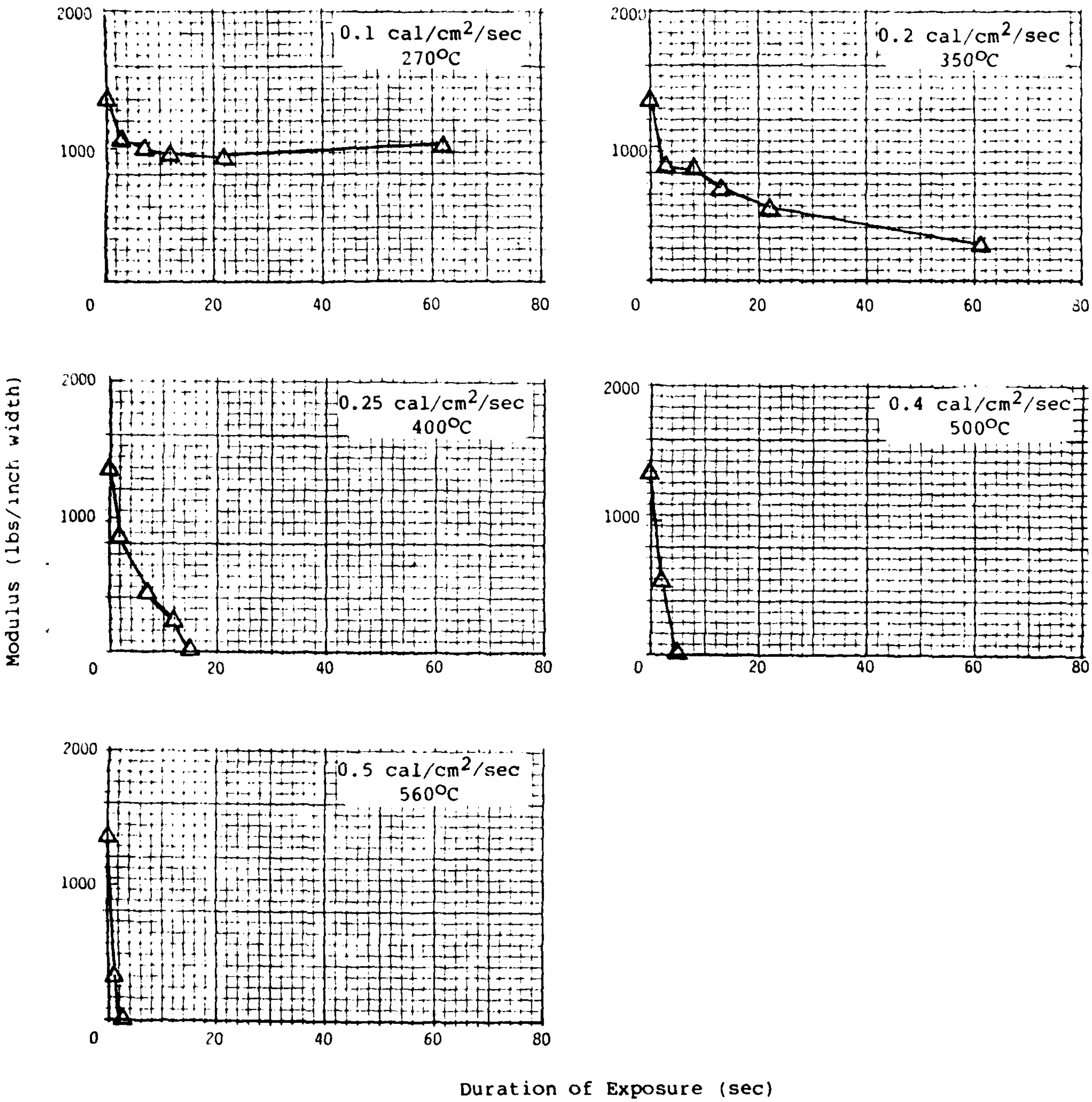
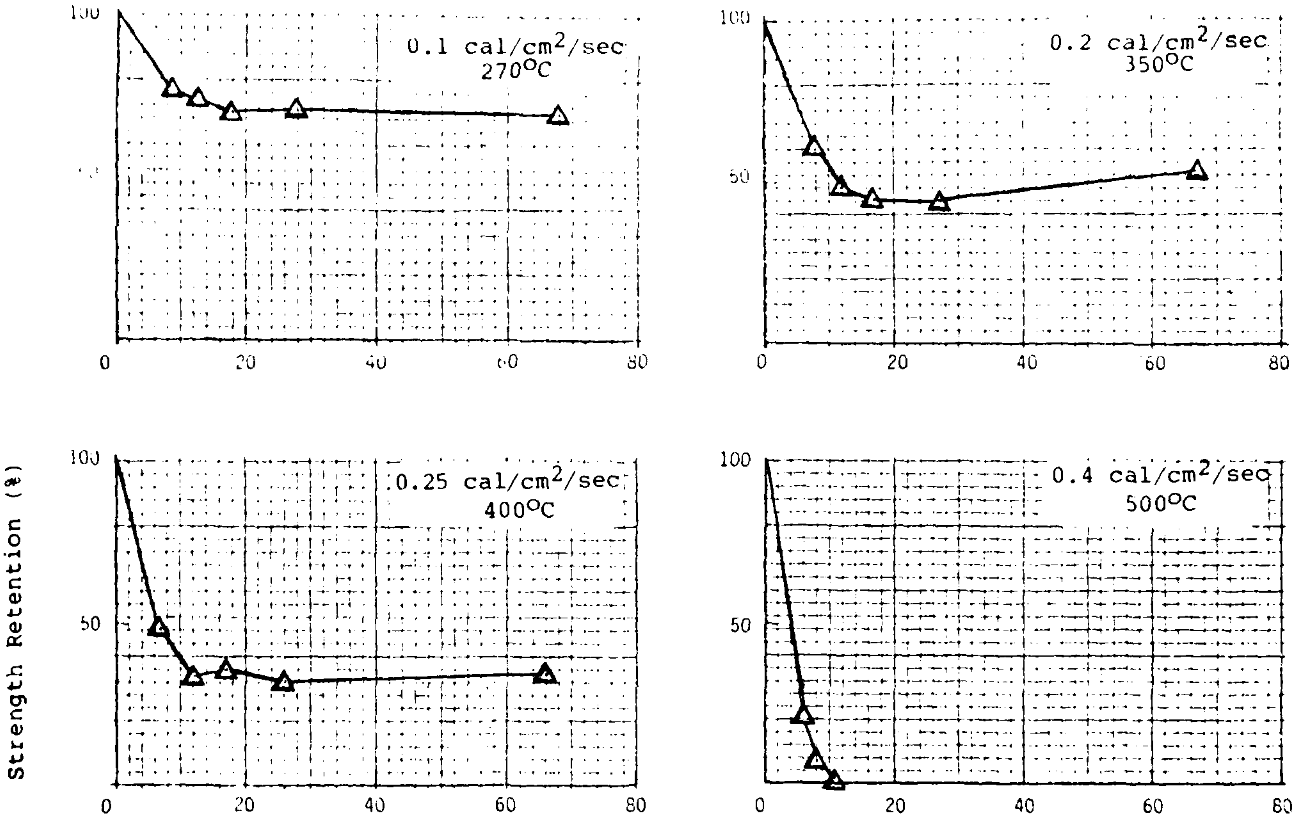
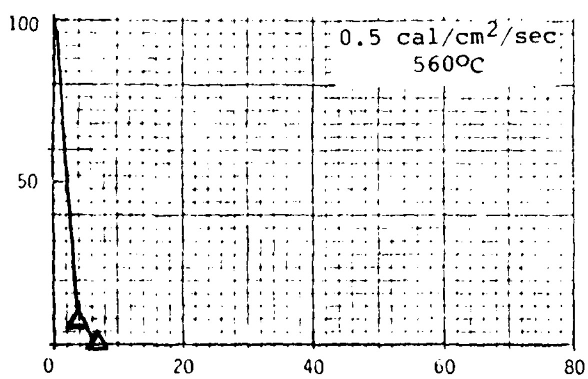


Figure 32b. Modulus of Fabric #16 (65/35 polyester/cotton blend, 5.8 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat





Heat Flux (cal/cm²/sec)	Time to Ignition (sec) Range	Average
0.1	---	---
0.2	---	---
0.25	---	---
0.4	---	---
0.5	No ignition, 2 min	
0.6	65-83	72
0.7	17-18	17

Duration of Exposure (sec)

Figure 33a. Strength Retention of Fabric #17 (95/5 Nomex/Kevlar, 4.6 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat

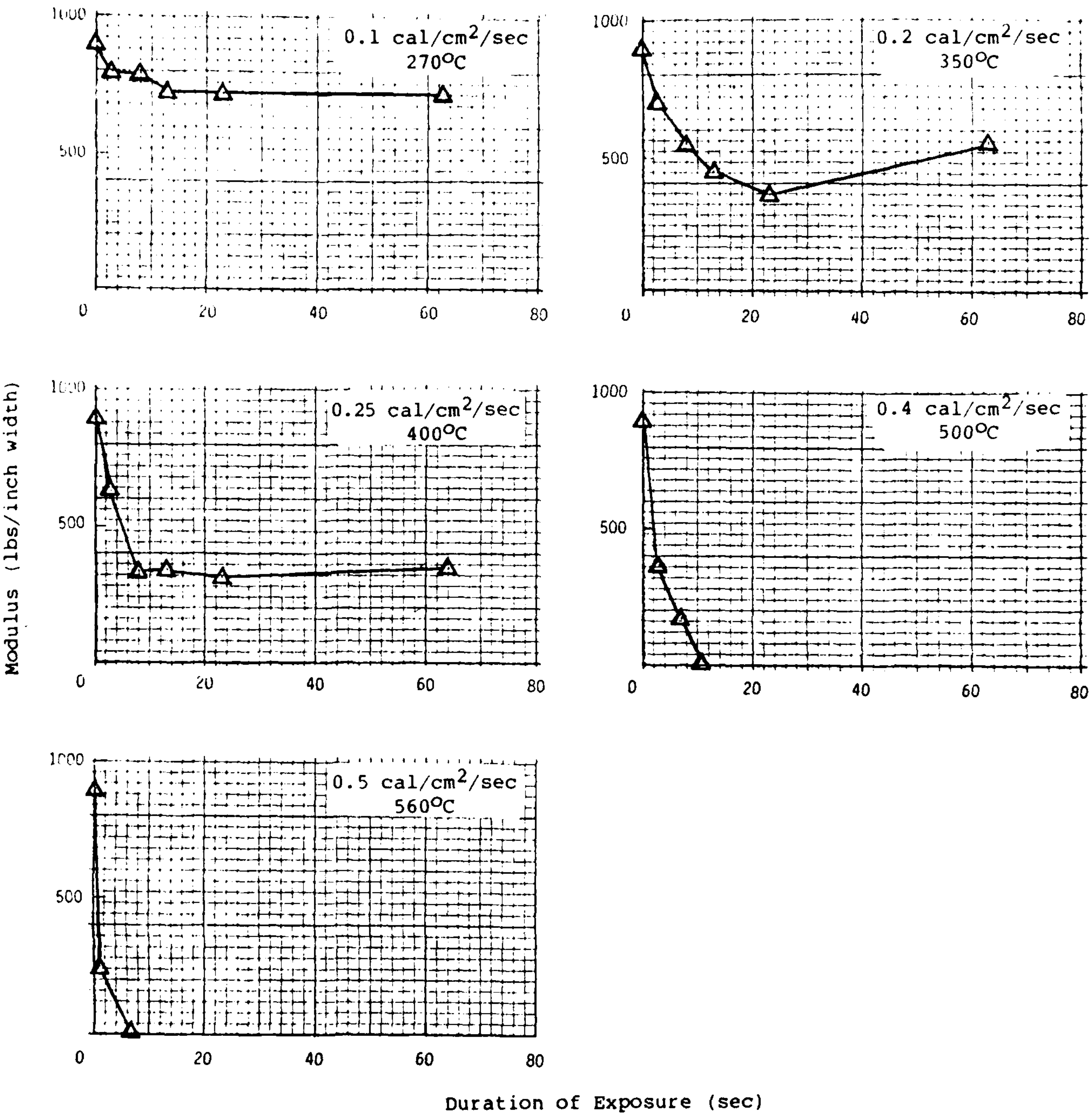
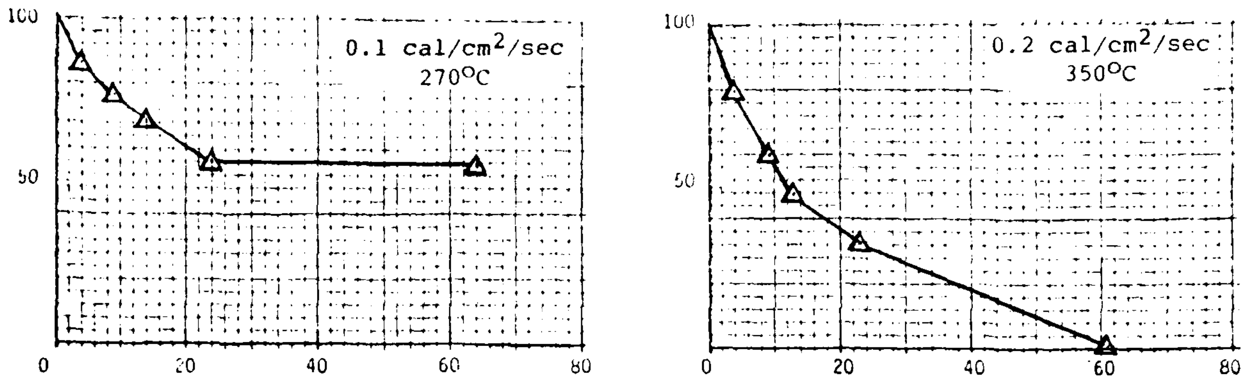
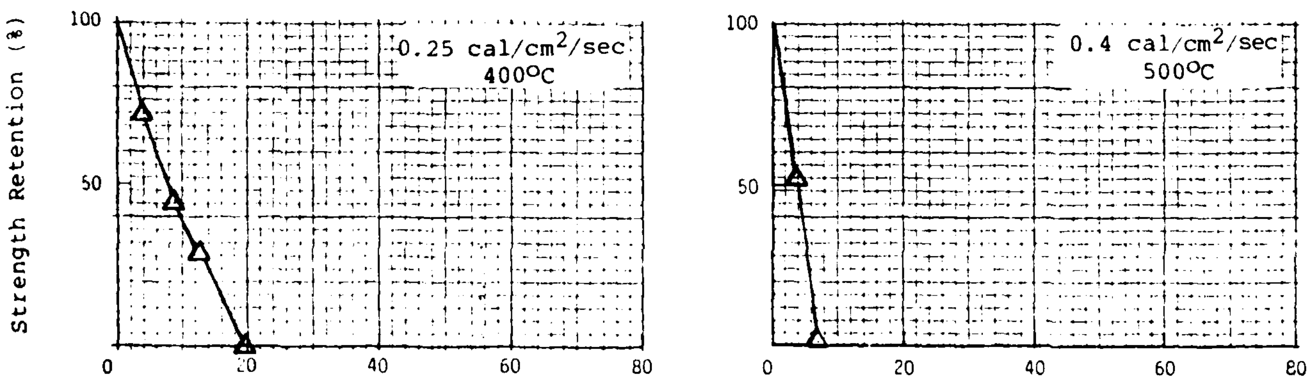
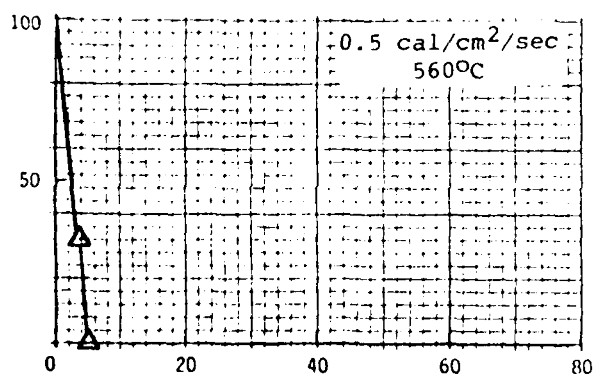


Figure 33b. Modulus of Fabric #17 (95/5 Nomex/Kevlar, 4.6 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat







Heat Flux ($cal/cm^2/sec$)	Time to Ignition (sec) Range	Average
0.1	---	---
0.2	---	---
0.25	No ignition, 2 min	
0.4	---	11 (only 2 of 10 specimens ignited)
0.5	5-7	6
0.6	---	4
0.7	3-4	3

Duration of Exposure (sec)

Figure 34a. Strength Retention of Fabric #18 (100% cotton FR, 6.9 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat

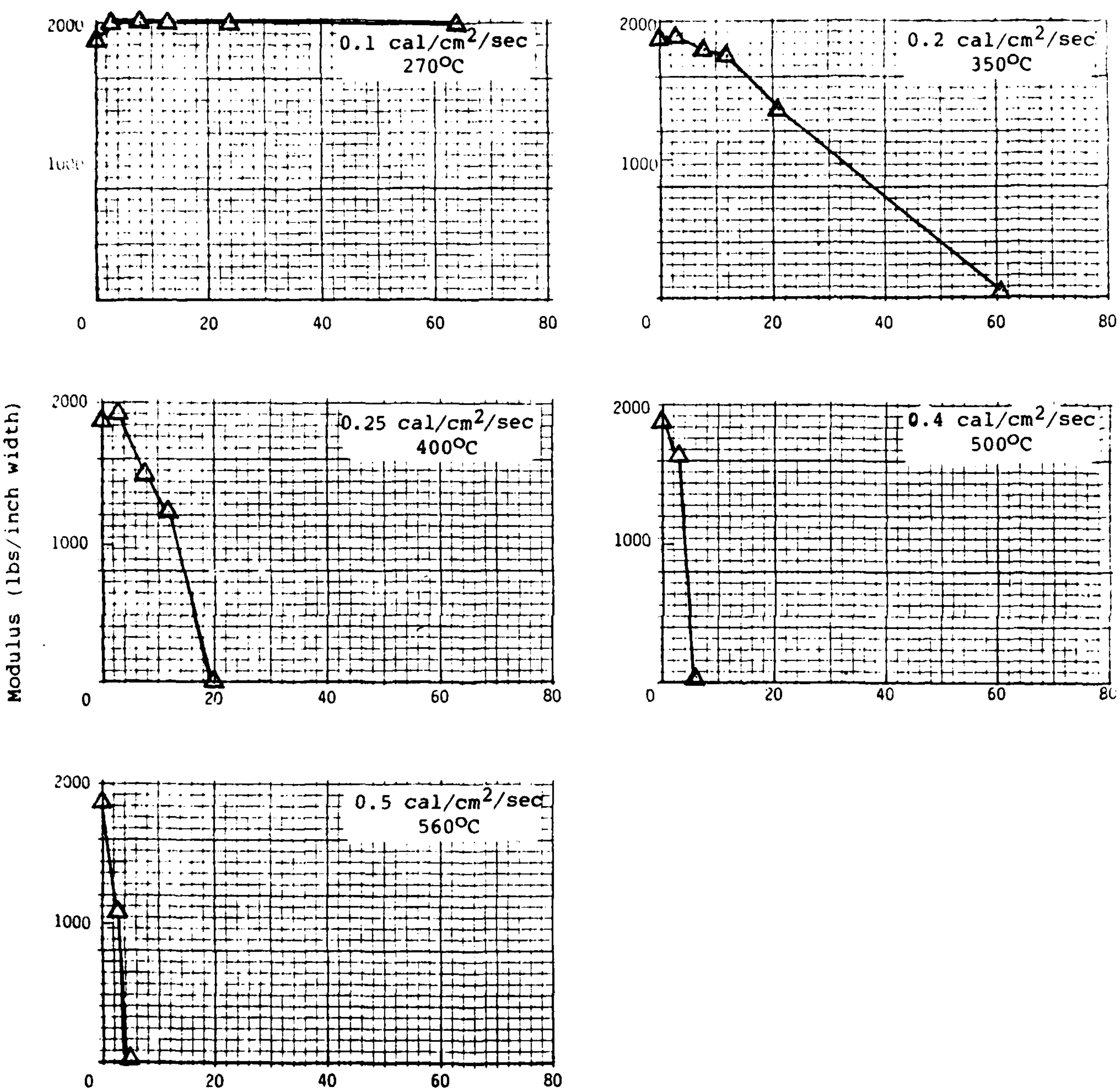


Figure 34b. Modulus of Fabric #18 (100% cotton FR, 6.9 oz/sq yd) During Exposure to Various Levels of Bilateral Radiant Heat

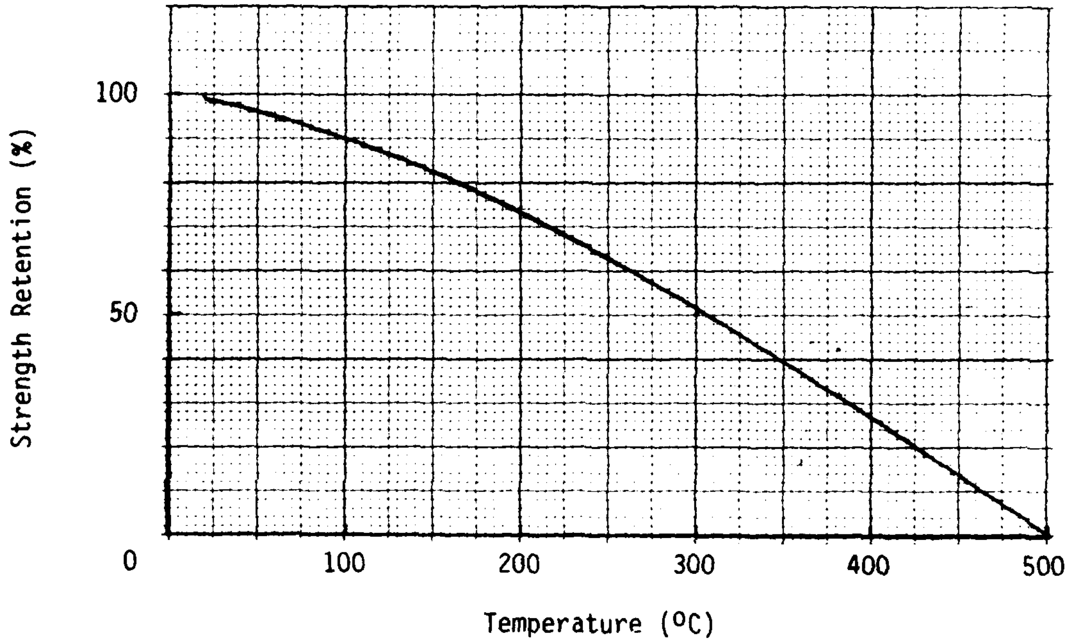


Figure 35. Hypothetical Relationship Between Fabric Strength Retention and Temperature

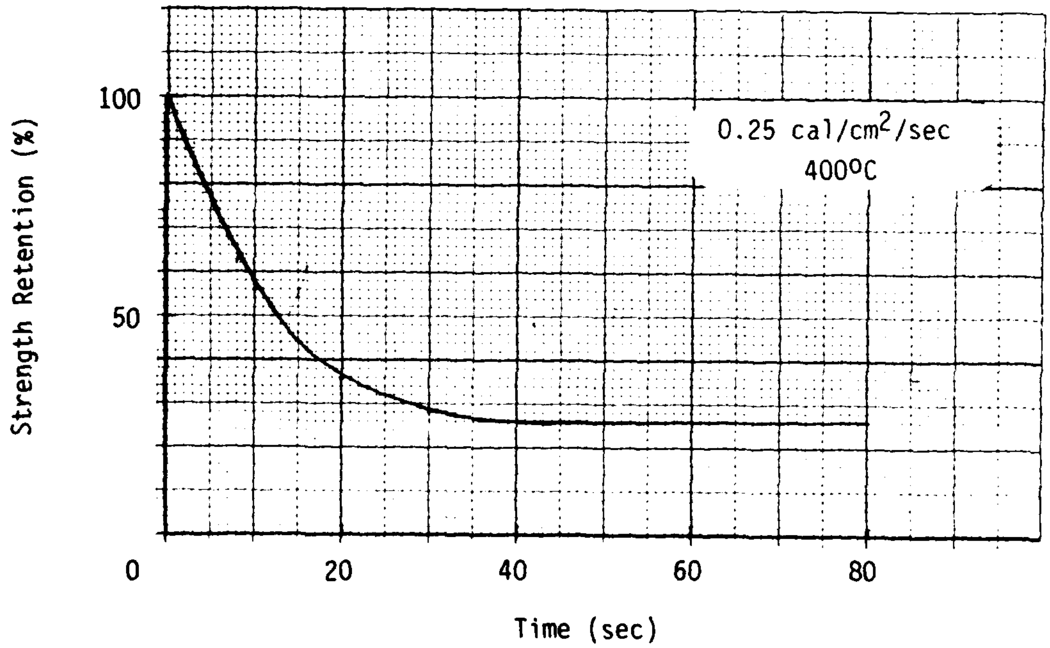


Figure 36. Theoretical Strength Retention-Time Curve for 6.0 oz/sq yd Fabric Derived from Figures 17 and 35

At heater surface temperatures of 500°C and above, all of the fabrics in the test group lose all strength within a few seconds after the start of exposure.

The tensile modulus-time curves given in Figure 18b through 34b often show the same trends as the strength retention curves - a fast initial drop followed by a more gradual decrease to an equilibrium level - but with greater exaggeration of perturbations caused by water vaporization, melting of thermoplastic polymer and, in some cases, additional cross-linking of the polymer. The latter is evidenced by reversals in the general downward trend of modulus with increasing exposure time as the temperature of the heating material increases (see Figure 33b). Since the tensile modulus decreases, in general, with increasing level of exposure, stiffening of the polymer structure does not occur; however, any loss in the relative mobility of fabric components, such as might be caused by adhesions formed between fibers or yarns during melting, might result in an increase in the bending stiffness of the fabric during exposure.

Because of large differences in weight per unit area among the fabrics of the test series, assessment of differences in thermal behavior related to material type cannot be achieved by direct comparison of fabric properties at particular exposure times. Since the time-to-temperature at any given radiant flux condition is directly proportional to the mass of material being heated (see Eq 7, AFML-TR-77-72), it seems reasonable to normalize the test results with respect to fabric weight. This involves altering the time scale of the strength loss data so that it is expanded for lighter weight fabrics and contracted for heavier ones. If we choose a fabric weight of 6.0 oz/sq yd as the norm, then the time scales should be multiplied by the ratio of 6.0 oz/sq yd to the actual weight of the fabric to place all of the test results on the same basis.

The normalized strength retention of the various fabric blends for 3- and 6-second exposures at 400°C, 500° and 560°C are plotted in histogram form in Figure 37, 38 and 39 respectively; where multiple fabrics of the same blend ratio were tested, these results were averaged. At exposures to 400°C a reasonably high level of strength is maintained by all of the fabrics tested during exposures to 6 seconds, as shown in Figure 37. The polyester/cotton blended fabrics higher in cotton content, the all-cotton fabrics (both normal and FR), the all-wool fabric, the nylon/cotton, the polyester/rayon, and the Nomex/Kevlar fabrics tested retain 50% or more of their original strengths at these conditions. At 500°C the same fabrics listed above retain significant strength for 3 seconds but for 6 seconds only the Nomex/Kevlar fabric retains a useful level of mechanical strength. At the still higher level of 560°C, all of the fabrics in the test series lose between 90 and 100% of their original strength with 6 seconds.

Although PBI was not included in the series of fabrics for evaluation under this program, test results available from previous government sponsored work have been included in the histograms[1,9]. In terms of short-term strength retention during exposure at heater temperatures to 560°C, PBI fabric is clearly superior to the other fabrics tested.

(Text continued on page 64.)

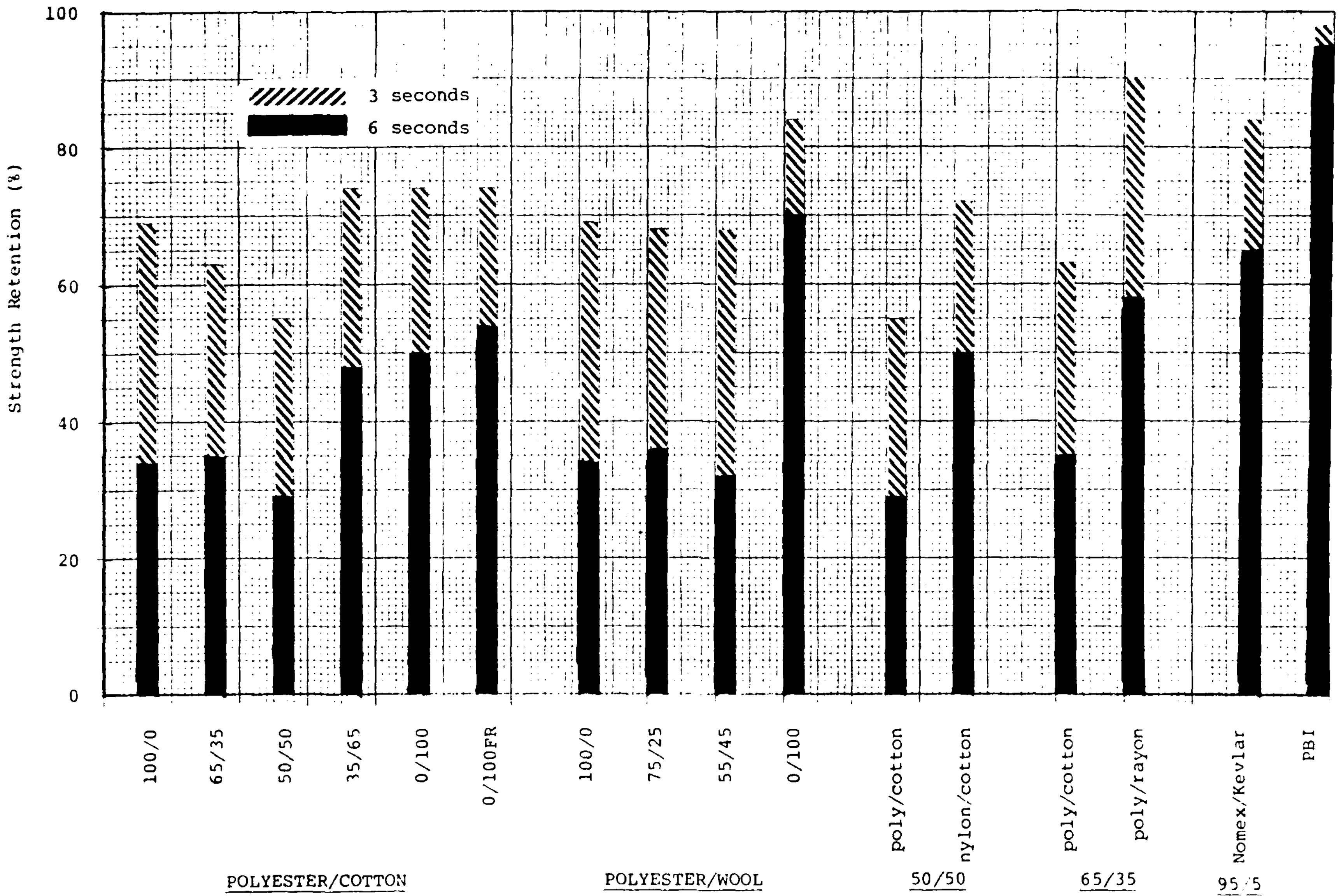


Figure 37. Strength Retention of Various Fabric Blends After 3-Second and 6-Second Exposures at 400°C ($0.25\ cal/cm^2/sec$) Normalized to a Fabric Weight of 6.0 oz/sq yd

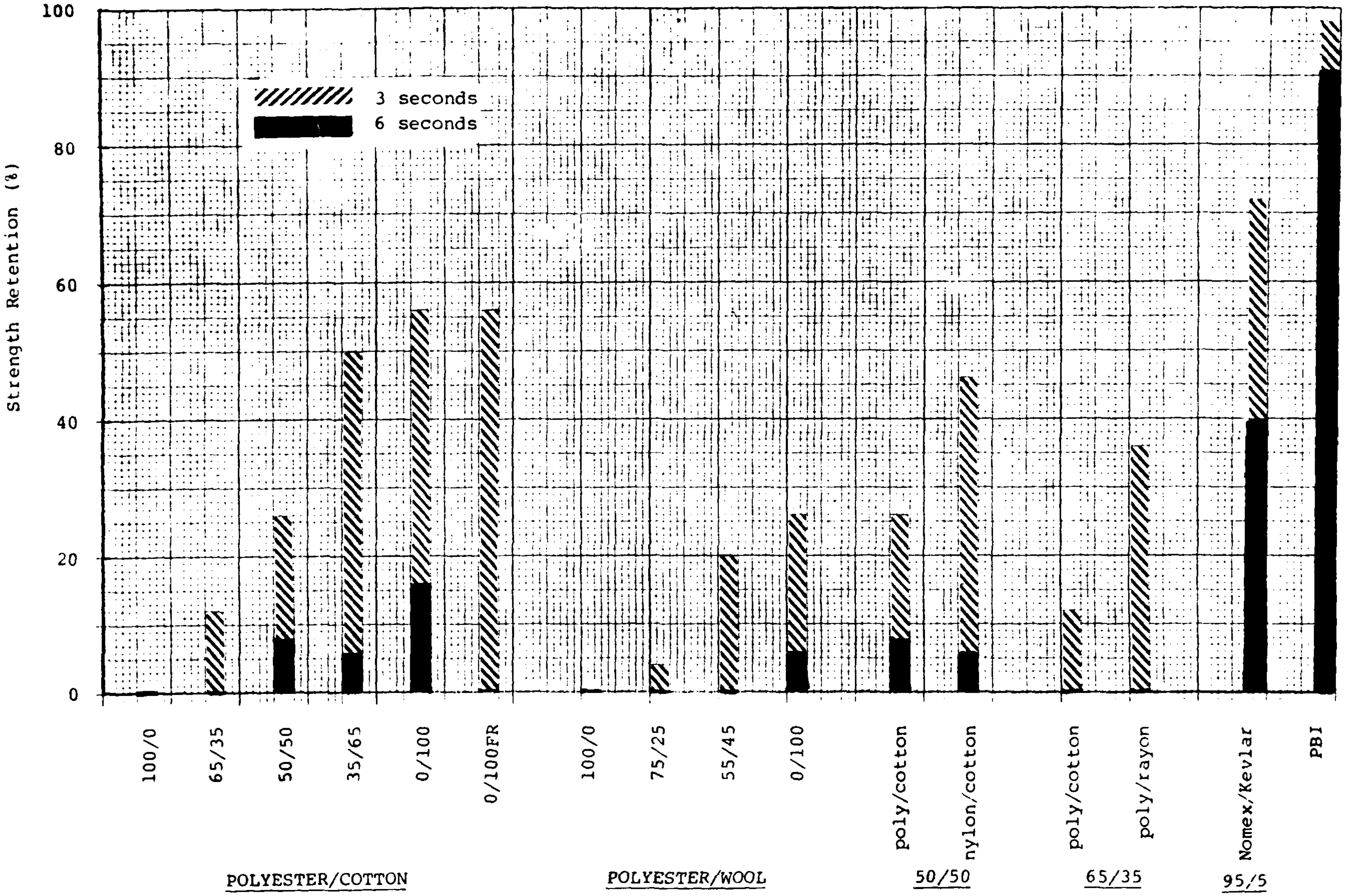


Figure 38. Strength Retention of Various Fabric Blends After 3-Second and 6-Second Exposures at 500°C ($0.4\ cal/cm^2/sec$) Normalized to a Fabric Weight of 6.0 oz/sq yd

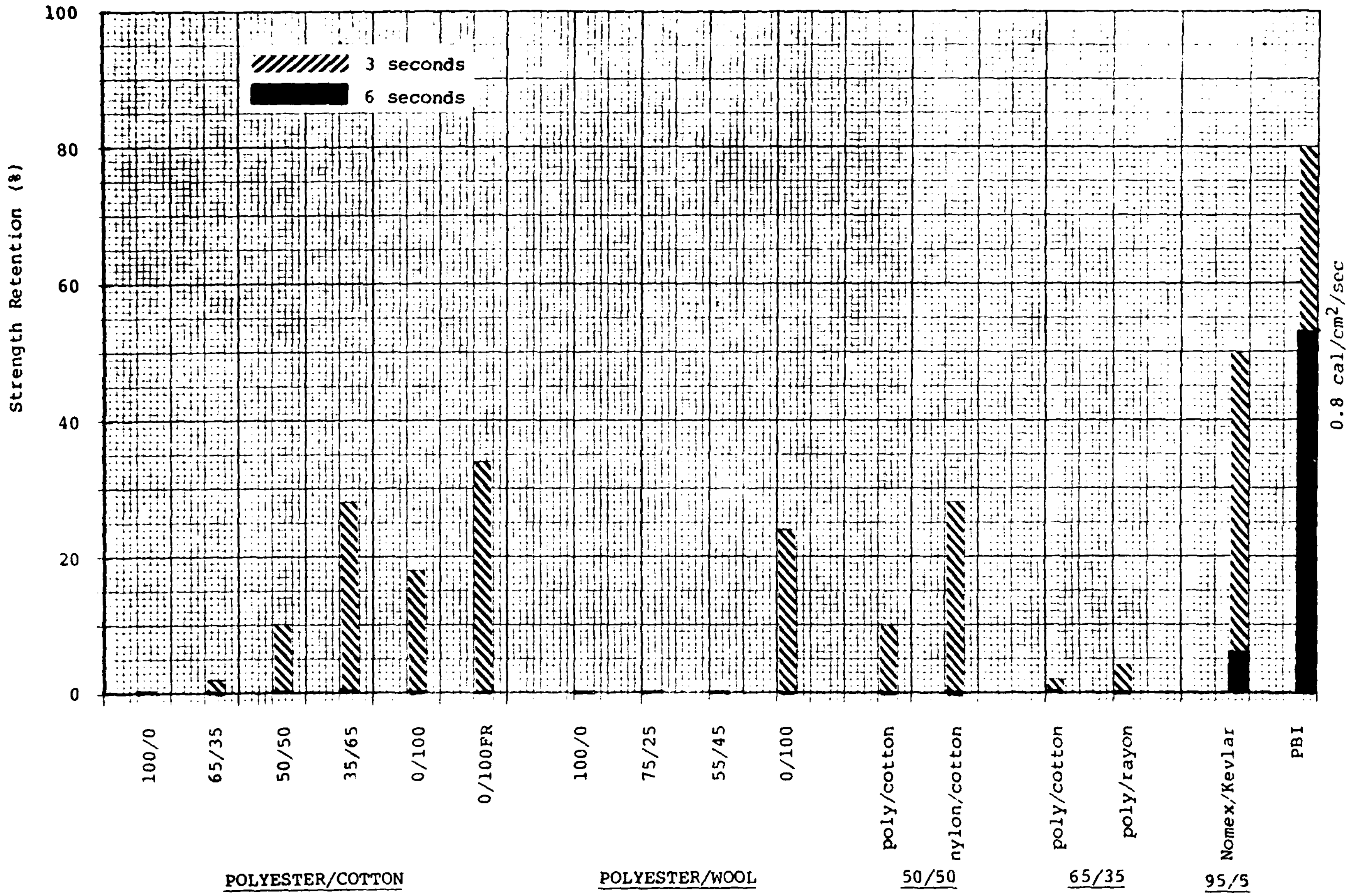


Figure 39. Strength Retention of Various Fabric Blends After 3-Second and 6-Second Exposures at 560°C ($0.5\ cal/cm^2/sec$) Normalized to a Fabric Weight of 6.0 oz/sq yd

Perhaps a more meaningful basis on which to compare the useful strength-retaining properties of the various fabric blends during exposure to radiant heat is the length of time required for the (normalized) strength to fall to the 10% level since at this level the fabrics can probably be expe... to retain some degree of integrity. The time to 90% strength loss for the different fabrics is compared in Figures 40, 41 and 42 for heat fluxes of 400°, 500° and 560°C respectively. As these graphs illustrate, a higher percentage of cotton or wool is desirable in the polyester blended fabrics. The FR treated cotton fabric retains strength for about the same length of time as the untreated cotton fabric. Nomex/Kevlar fabric offers a significant time advantage at 400°C, less at 500°C and virtually none at 560°C. The PBI fabric offers a greater advantage than the Nomex/Kevlar at temperatures to 560°C.

C. Ignition Properties

The time required for single-layers of the fabrics in the test series to ignite spontaneously during exposure to bilateral radiant heat at various levels is summarized in the tables contained in Figures 18a through 34a; individual test results are collected in Appendix Table 2. Such data should be used only to compare the ignition properties of the various fabrics when measured under the same test conditions and may not relate well to ignition behavior determined under other circumstances since it is well known that ignition is a path-dependent event affected by mode and rate of heating, specimen size and position, rate of air flow, oxygen availability and the criteria used to determine the onset of ignition. In the present case the point of ignition was taken as the first appearance of a flame; in some cases a glow preceded or occurred instead of a flame and this is noted in the Appendix Table 2; the level of smoke generation is also noted in the Appendix table.

As with comparisons of strength retention, the times-to-ignition of the various fabrics have been normalized to a fabric weight of 6 oz/sq yd and presented in histogram form in Figures 43-45. The data presented in these figures show the consistent merits of polyester/wool, 100% wool, Nomex/Kevlar and PBI in delaying ignition at exposure temperatures to 650°C. Either a high or a low fraction of polyester in the polyester/cotton and polyester/wool blends seems preferable to intermediate levels. Surprisingly, the FR treated cotton fabric ignites in somewhat less time than the untreated cotton fabrics at each of the test temperatures to 650°C. The Nomex/Kevlar and PBI fabrics are inherently less flammable than the other materials tested at temperatures to 650°C although this advantage is likely to dissipate at higher temperatures.

Examination of the summarized ignition time data for each of the six individual 65/35 polyester/cotton blended fabrics and for the three 100% cotton fabrics contained in Table 3 gives some insight into the effect of parameters other than material type and fabric weight on response to radiant heat. For example, among the 65/35 blends the normalized average ignition times are unusually high for fabric 20; this particular fabric, a knit, also has a thickness-to-weight ratio approximately twice that of the other five fabrics in this group. The effect of fabric thickness can also be seen among the results for all-cotton fabrics where the normalized ignition times rank in the same order as the thickness-to-weight ratios. Thickness is, of course, the primary parameter affecting heat flow rate by conduction to the interior of the fabric structure, and although most of the fabrics in the test series may be considered optically thin, those more open structures in which the mass is concentrated in relatively large diameter yarns may be expected to show more of a time effect associated with delay of penetration of heat to the interior of the yarn. Fabric color seems to have a minimal effect on time to ignition: the white 65/35 fabric 22 exhibits virtually the same times to ignition as the medium blue fabric 12 and only slightly longer times than the dark, navy blue fabric 16 (all three fabrics having approximately the same thickness-to-weight weight ratio).

(Text continued on page 73.)

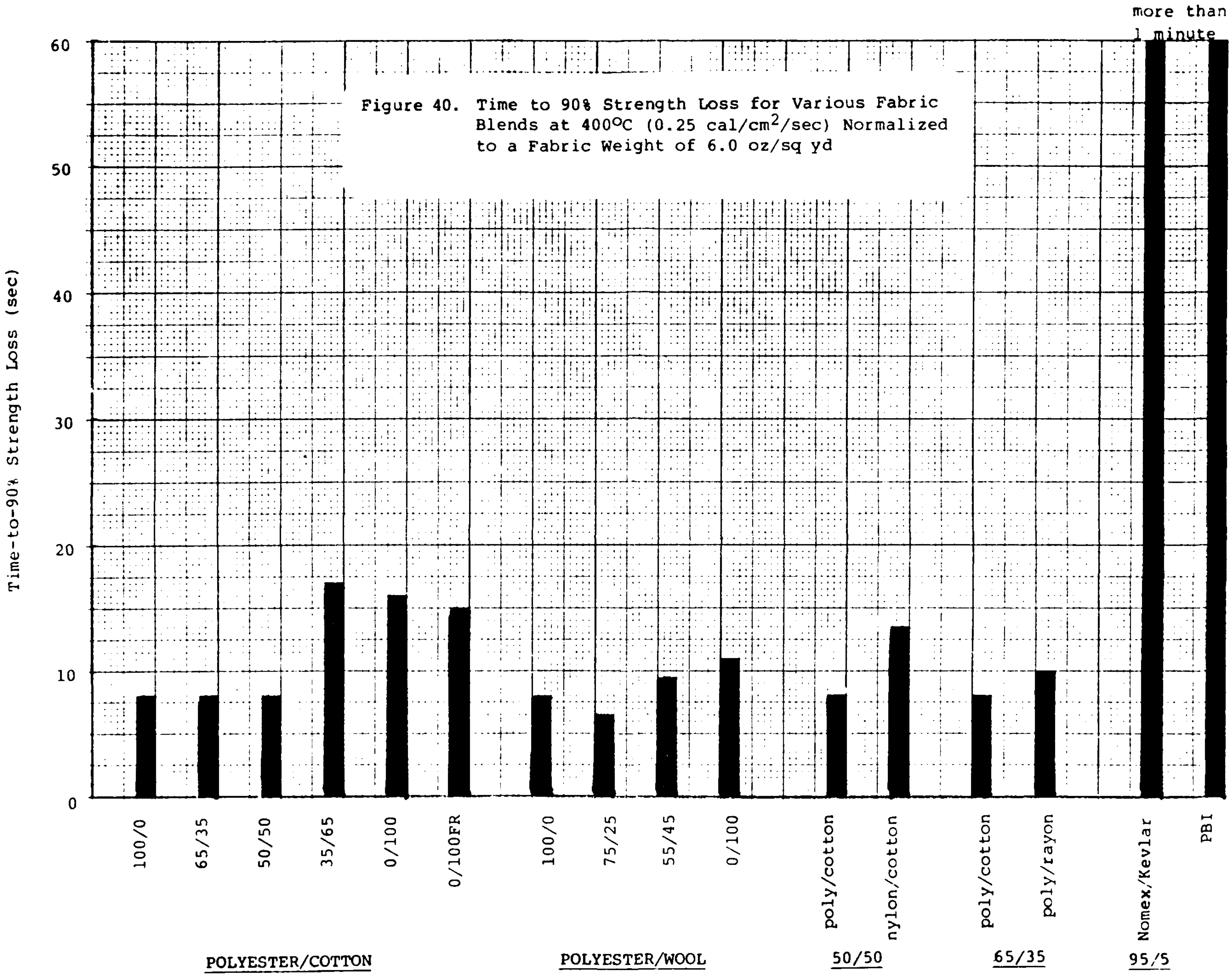


Figure 40. Time to 90% Strength Loss for Various Fabric Blends at 400°C (0.25 $cal/cm^2/sec$) Normalized to a Fabric Weight of 6.0 oz/sq yd

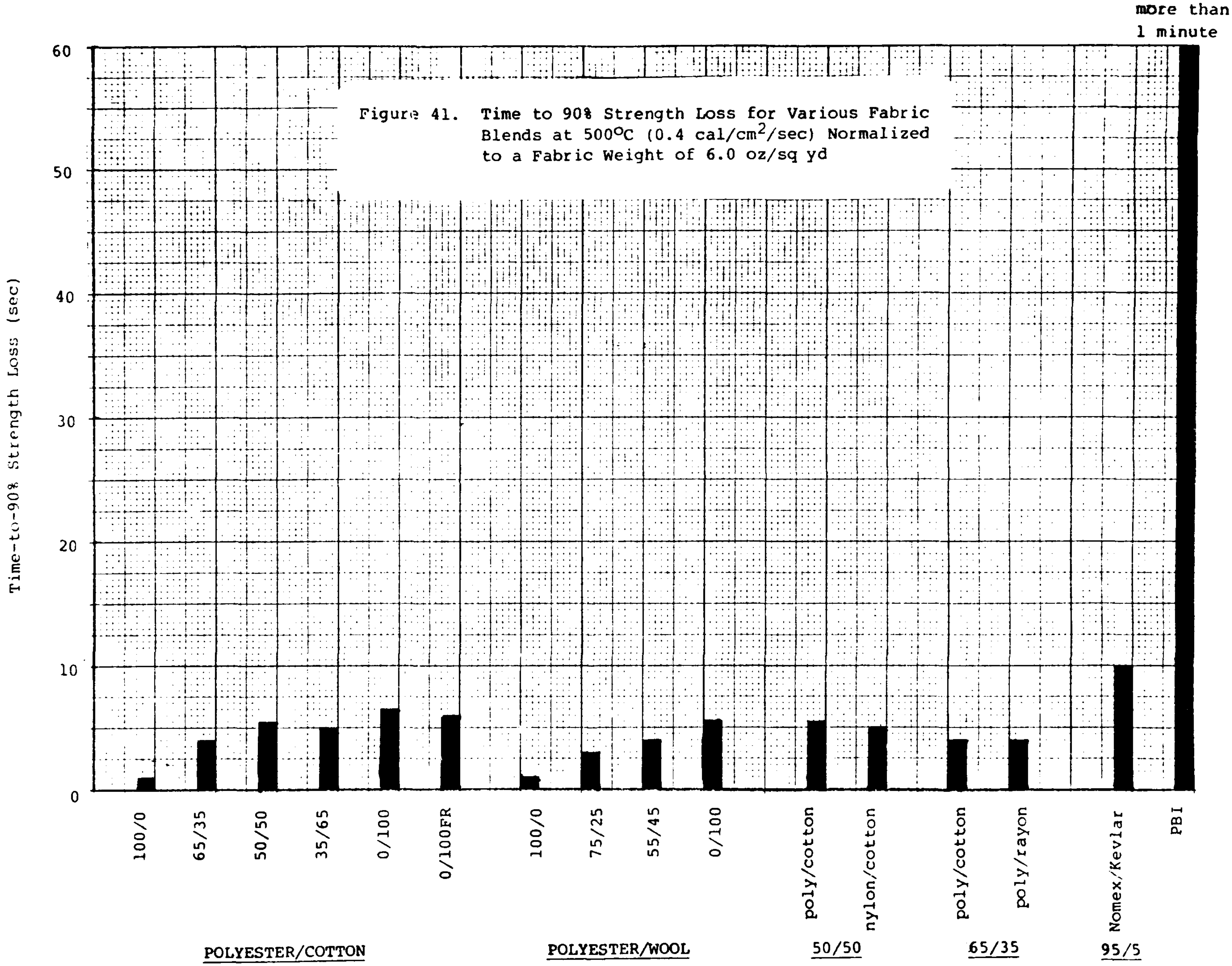
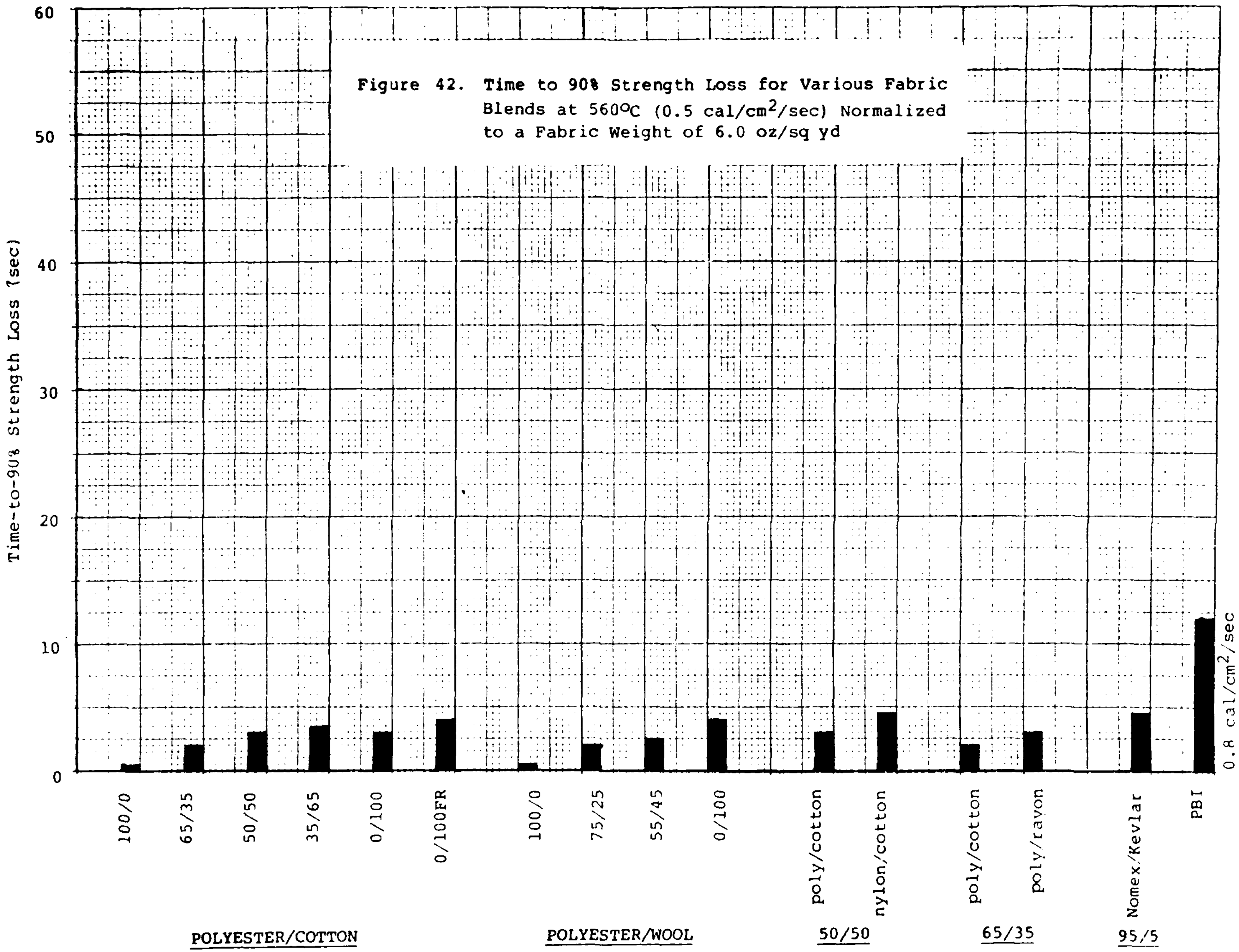


Figure 41. Time to 90% Strength Loss for Various Fabric Blends at 500°C (0.4 cal/cm²/sec) Normalized to a Fabric Weight of 6.0 oz/sq yd

Figure 42. Time to 90% Strength Loss for Various Fabric Blends at 560°C (0.5 cal/cm²/sec) Normalized to a Fabric Weight of 6.0 oz/sq yd



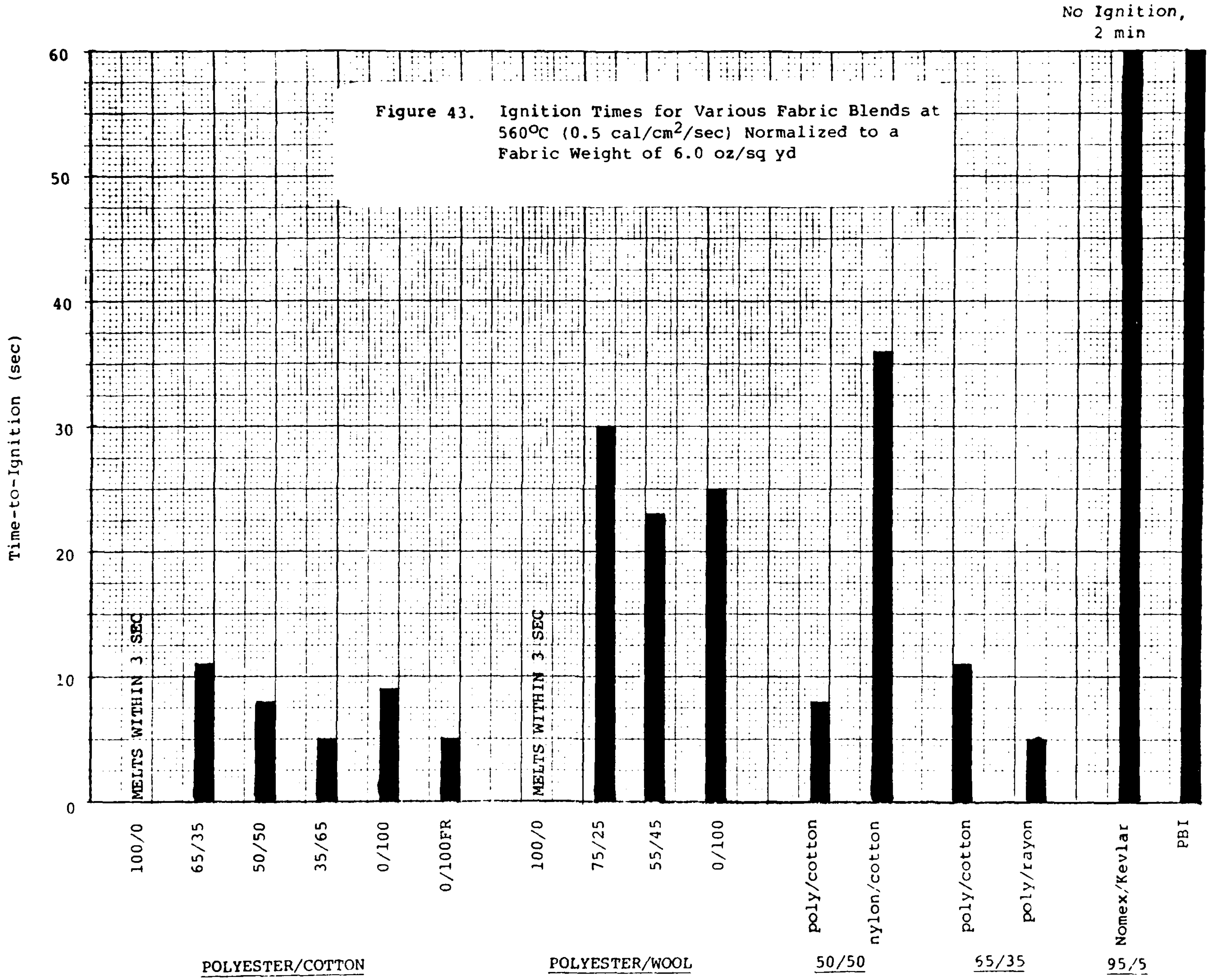


Figure 43. Ignition Times for Various Fabric Blends at 560°C (0.5 cal/cm²/sec) Normalized to a Fabric Weight of 6.0 oz/sq yd

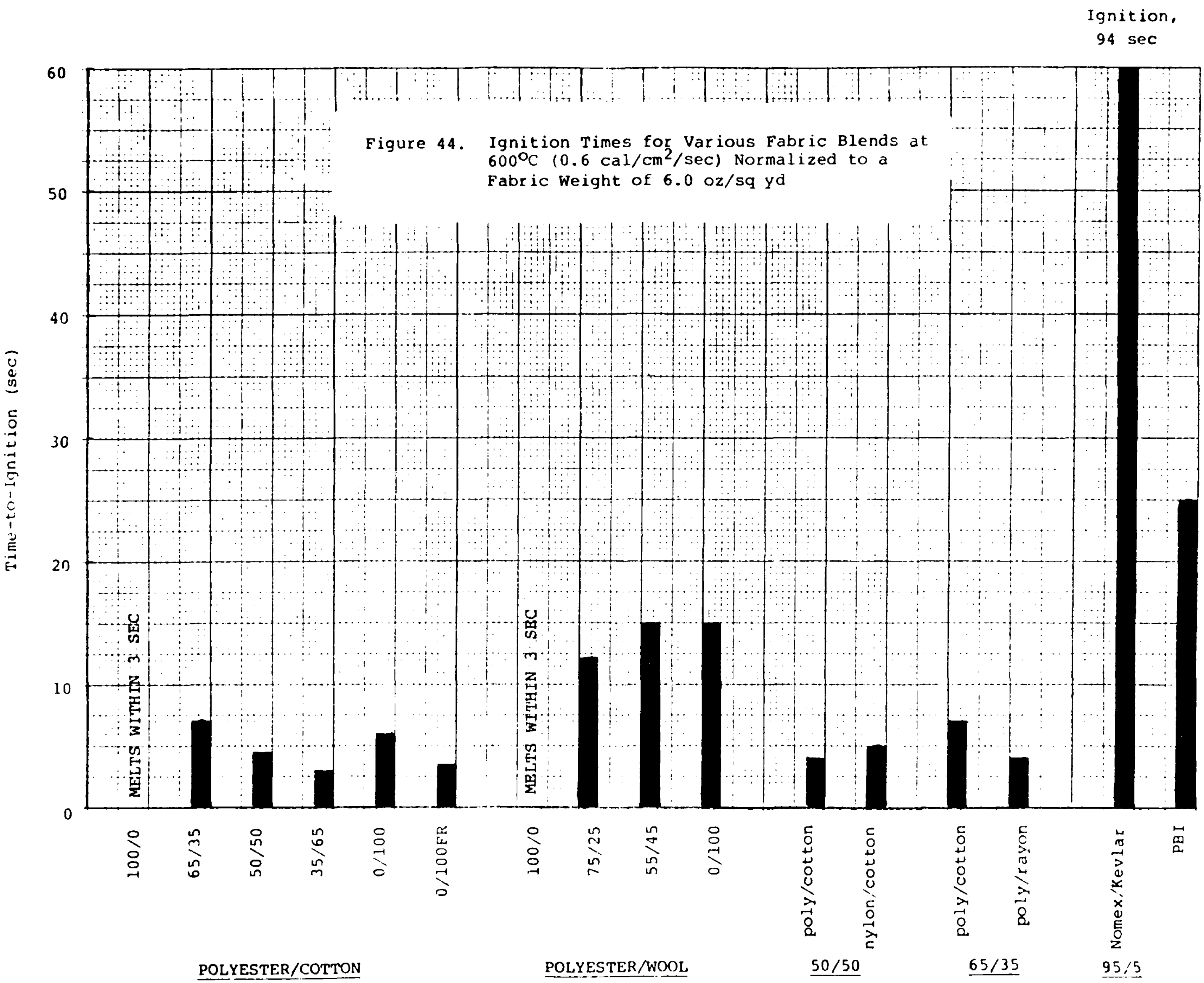


Figure 44. Ignition Times for Various Fabric Blends at 600°C (0.6 cal/cm^2/sec) Normalized to a Fabric Weight of 6.0 oz/sq yd

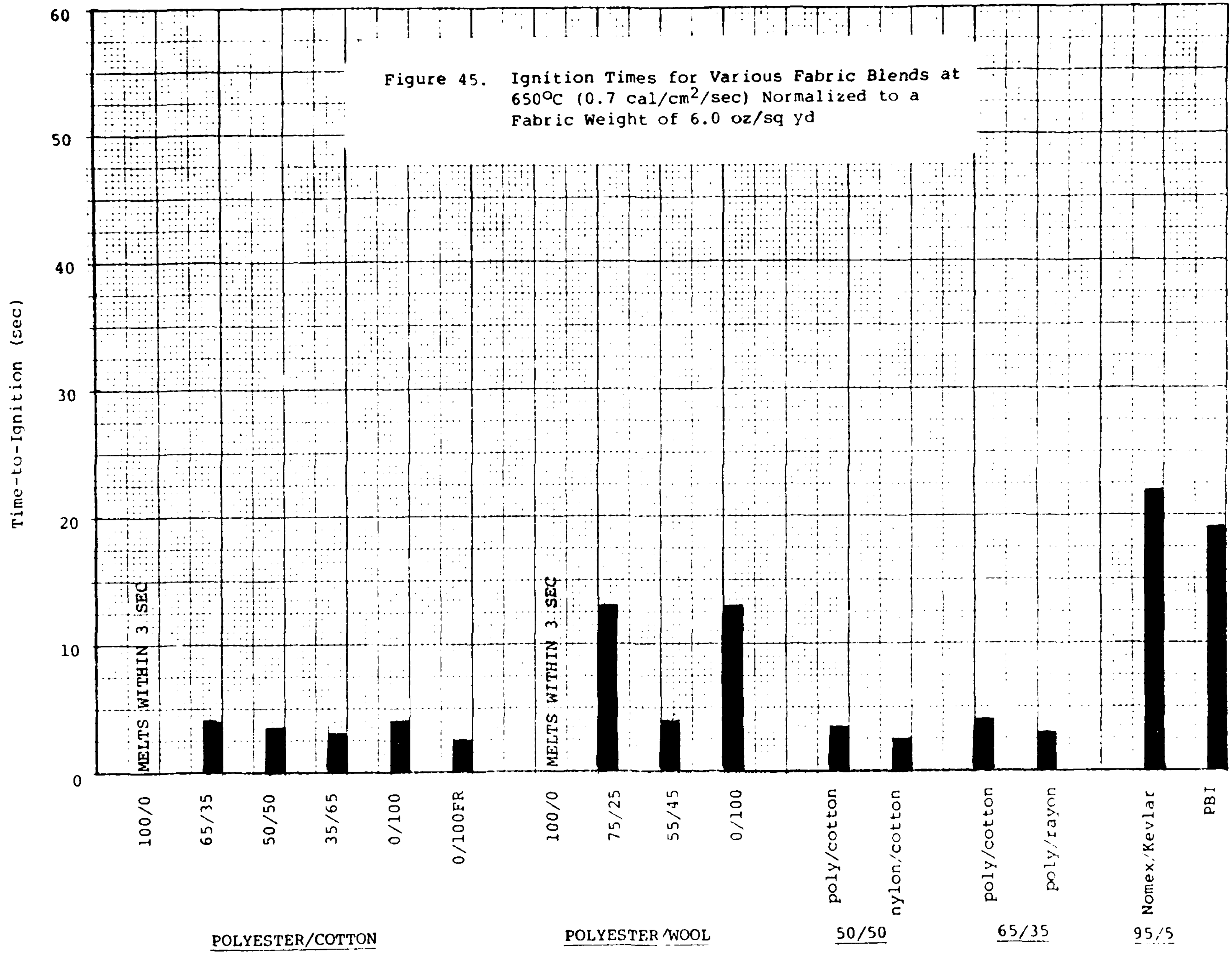


Figure 45. Ignition Times for Various Fabric Blends at 650°C (0.7 cal/cm^2/sec) Normalized to a Fabric Weight of 6.0 oz/sq yd

Table 3. Comparative Ignition roperties of Fabrics of Same Fiber Content

Fabric No.	Blend Ratio	Weight (oz/sq yd)	Thickness (inch)	Thickness/Weight Ratio [10^3 x inch/(oz/sq yd)]	Color	Heat Flux (cal/cm^2/sec)	Time-to-Ignition (sec) Actual	Time-to-Ignition (sec) Normalized to 6.0 oz/sq yd
POLYESTER/COTTON:								
6	65/35	7.0	0.016	2.3	khaki	0.5	14	12
						0.6	8	7
						0.7	3	2.5
16	65/35	5.8	0.016	2.8	navy	0.5	7	7
						0.6	4	4
						0.7	2	2
12	65/35	4.8	0.013	2.7	medium blue	0.5	7	9
						0.6	5	6
						0.7	3	4
15	65/35	4.4	0.011	2.5	khaki	0.5	8	11
						0.6	4	5.5
						0.7	3	4
20	65/35	3.4	0.018	5.3	white	0.5	11	19
						0.6	7	12
						0.7	4	7
22	65/35	3.0	0.008	2.7	white	0.5	4	8
						0.6	3	6
						0.7	2	4
100% COTTON (untreated):								
3	0/100	10.3	0.029	2.8	denim blue	0.5	7	4
						0.6	6	3.5
						0.7	5	3
19	0/100	3.6	0.019	5.3	white	0.5	9	15
						0.6	6	10
						0.7	3	5
21	0/100	3.2	0.011	3.4	white	0.5	5	9
						0.6	3	5.5
						0.7	2	4

IV. RADIANT HEAT TRANSFER

In order to assess the extent of protection to the skin provided by the various work clothing fabrics and fabric assemblies from the direct penetration of radiant heat, measurements were made of the amount of heat transferred from unilaterally irradiated fabric strips to an underlying surface. For this measurement a single quartz heater panel and a water-cooled copper calorimeter were employed as illustrated in Figure 46. The calorimeter is embedded flush with the surface of a black transite board on which the fabric test strip is mounted. At the start of exposure the preheated panel, mounted on a track, is quickly pulled into place facing the fabric strip. The voltage output of the calorimeter, proportional to impinging heat flux, is recorded continuously for the next 60 seconds. If ignition occurs during this time, the panel is pushed away while the calorimeter continues to monitor the heat flux from the burning fabric. Incident heat flux is determined separately with no fabric specimen in place. The total heat flux transferred from the fabric to the surface of the calorimeter is expressed as a percentage of the heat flux incident on the surface of the fabric.

Fabric response was determined at three unilateral heat flux levels: 0.4, 0.75 and 1.25 cal/cm^2/sec corresponding to internal heater temperatures of 650°C, 800°C and 1000°C respectively. Each of the fabrics, including the 17 outerwear fabrics and the four underwear fabrics, were tested as a single layer; 48 outerwear/underwear fabric assemblies were also characterized. Ignition of some of the fabrics occurred during the first 60 seconds of exposure at 0.75 cal/cm^2/sec, while all of the materials ignited at the 1.25 cal/cm^2/sec level. Table 4 contains a summary of the heat transfer and ignition behavior of the various fabrics and fabric assemblies based on the responses of three specimens of each type; maximum heat transfer during the first 10 seconds of exposure, as a percentage of incident heat flux, is noted as is the maximum heat transferred after ignition. The response of the outerwear fabrics tested as single layers is more fully described in Appendix Table 3. Since essentially no difference was found between the behavior of those assemblies containing a particular outerwear fabric and either all cotton or 65/35 polyester/cotton underwear fabrics of the same construction - knit or woven - data for the assemblies containing the two knit underwear fabrics were combined in Table 4 as were data for assemblies containing the two woven underwear fabrics. Typical traces of the calorimeter output, again expressed as a percentage of incident heat flux, are presented in Figure 47 for a single layer of fabric 16 and in Figure 48 for a fabric assembly consisting of fabric 16 and knit underwear fabric. The response tended to be somewhat variable within the group of three replicate specimens of each fabric or assembly type tested at each condition depending on the extent of specimen shrinking and curling away from the calorimeter. However, the data in Table 4 represents a reasonable estimate of the worst case conditions. In general, an initial peak in heat transfer was followed by a more gradual rise to a steady level or, if ignition occurred, it was followed by a sharper and more intense peak as the burning fabric itself gave off considerable quantities of heat.

(Text continued on page 79.)

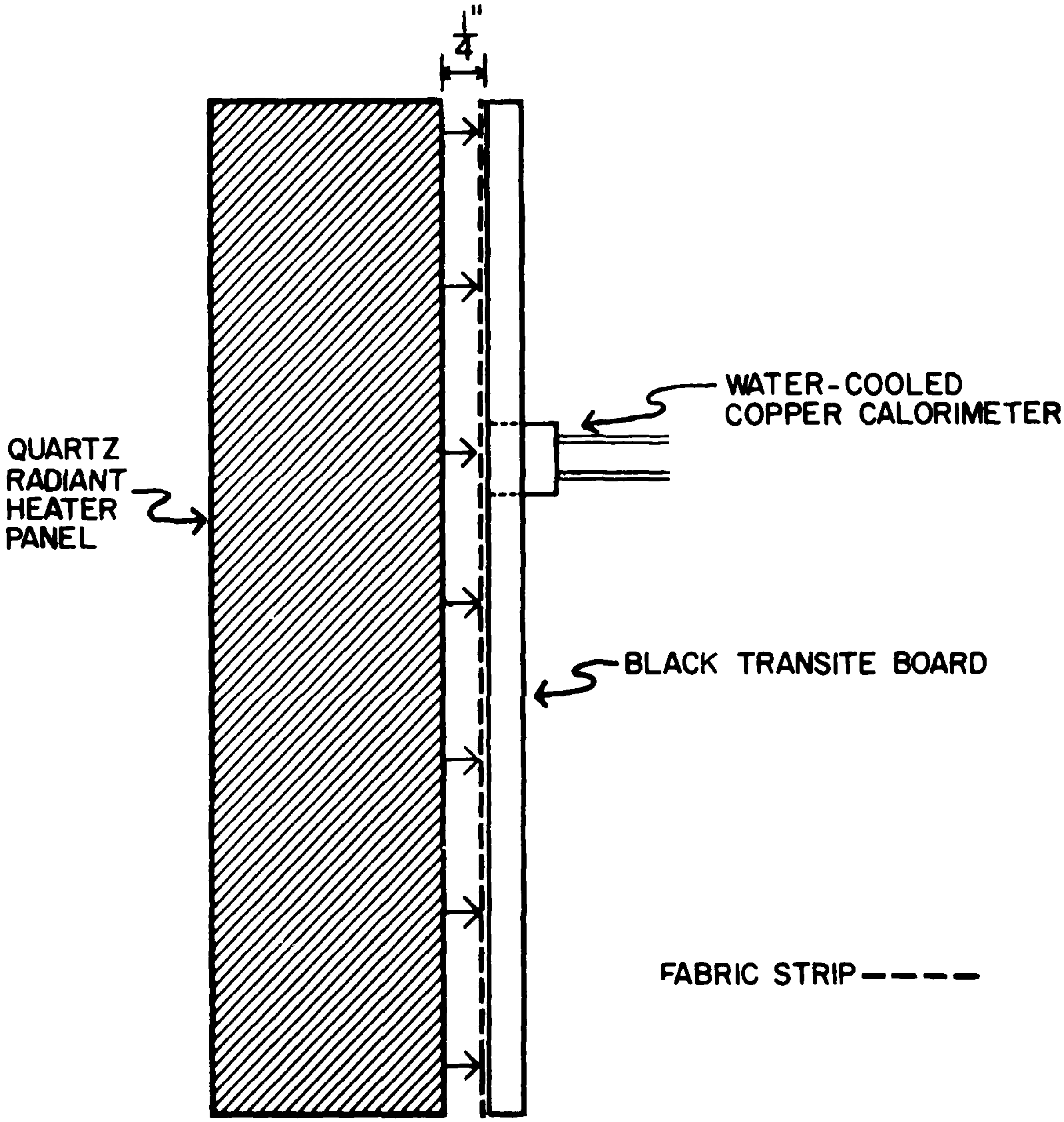


Figure 46. Test Configuration for Radiant Heat Transfer Measurements

Table 4. Summary of Heat Transfer to an Underlying Surface from Fabric Assemblies Exposed to Various Radiant Heat Flux Levels

Outerwear Fabric No.	Outerwear Blend Ratio	Underwear Fabric No.	Underwear Fabric Type	Assembly Weight (oz/sq yd)	Light Transmission (%)	Maximum Heat Transfer in First 10 Seconds of Exposure (%)			Time of Ignition (sec)		Maximum Heat Transfer after Ignition (%)	
						0.4 cal/ cm^2/sec	0.75 cal/ cm^2/sec	1.25 cal/ cm^2/sec	0.75 cal/ cm^2/sec	1.25 cal/ cm^2/sec	0.75 cal/ cm^2/sec	1.25 cal/ cm^2/sec
POLYESTER/COTTON BLENDS:												
13	100/0	single layer, outerwear only		6.0	1.5	60	100	150	melted	3-4	--	150
		20, 19	knit	9.4-9.6		40	100	30	12-37	4-5	85	55
		22, 21	woven	9.0-9.2		60	55	30	13-15	3-4	90	40
9	100/0	single layer, outerwear only		6.0	3.2	60	100	135	melted	3-4	--	135
		20, 19	knit	9.4-9.6		56	70	55	10-42	1-6	120	90
		22, 21	woven	9.0-9.2		37	60	30	13-18	2-3	260	80
6	65/35	single layer, outerwear only		7.0	6.5	50	60	40	---	5-6	--	30
		22, 21	woven	10.0-10.2		45	45	25	---	4	--	25
16	65/35	single layer, outerwear only		5.8	0.6	80	180	40	8-12	4	180	30
		20, 19	knit	9.2-9.4		40	30	40	10-15	4-5	130	45
		22, 21	woven	8.8-9.0		45	50	25	13	3-4	170	50
12	65/35	single layer, outerwear only		4.8	7.3	80	60	50	---	4	--	50
		20, 19	knit	8.2-8.4		35	40	30	14-26	4-5	90	30
15	65/35	single layer, outerwear only		4.4	14.8	40	70	70	---	4	--	70
		20, 19	knit	7.8-8.0		45	40	30	11-37	3-4	85	30
single layer, underwear only		19, 20	knit	3.4-3.6	28.4-40.0	60	80	70	9-15	1-2	145	80
single layer, underwear only		21, 22	woven	3.0-3.2	37.7-39.2	90	125	165	8-10 (Fabric #22 only)	3-4	125	165
7	50/50	single layer, outerwear only		6.9	23.9	45	90	150	12-26	4	300	150
		22, 21	woven	9.9-10.1		40	50	30	---	4-6	--	30
11	50/50	single layer, outerwear only		3.5	27.0	50	60	120	---	3-4	--	120
		20, 19	knit	6.9-7.1		40	35	35	14-21	3-4	90	55
1	35/65	single layer, outerwear only		10.3	0.3	50	60	50	15-29	5	140	70
		22, 21	woven	13.3-13.5		40	40	20	22-35	4-6	120	70
3	0/100	single layer, outerwear only		10.3	0.3	90	50	70	21-22	5-7	100	70
		22, 21	woven	13.3-13.5		50	50	40	19-26	5-8	80	45
18	0/100 FR	single layer, outerwear only		6.9	0.3	30	150	190	---	4	--	190
		20, 19	knit	10.3-10.5		30	135	65	---	5	--	65
		22, 21	woven	10.1-10.3		35	115	55	---	5	--	55

Table 4. Summary of Heat Transfer to an Underlying Surface from Fabric Assemblies Exposed to Various Radiant Heat Flux Levels (cont)

Outerwear Fabric No.	Outerwear Blend Ratio	Underwear Fabric No.	Underwear Fabric Type	Assembly Weight (oz/sq yd)	Light Transmission (%)	Maximum Heat Transfer in First 10 Seconds of Exposure (%)			Time of Ignition (sec)		Maximum Heat Transfer after Ignition (%)	
						0.4 cal/ cm^2/sec	0.75 cal/ cm^2/sec	1.25 cal/ cm^2/sec	0.75 cal/ cm^2/sec	1.25 cal/ cm^2/sec	0.75 cal/ cm^2/sec	1.25 cal/ cm^2/sec
POLYESTER/WOOL BLENDS:												
8	75/25	single layer, outerwear only		6.4	2.6	40	75	130	35 (only 2 of 3)	6-10	350	130
		20, 19	knit	9.8-10.0		45	45	50	---	5-10	--	50
		22, 21	woven	9.4-9.6		40	50	25	---	4-5	--	80
2	55/45	single layer, outerwear only		6.4	1.2	50	60	35	---	7-13	--	120
		22, 21	woven	9.4-9.6		50	40	30	---	6-10	--	75
14	0/100	single layer, outerwear only		8.4	0.3	40	70	50	---	16-22	--	40
		20, 19	knit	11.8-12.0		40	55	35	---	20-50	--	30
		22, 21	woven	11.4-11.6		40	55	30	---	10-60	--	30
OTHER BLENDS:												
4	50/50 nylon/cotton	single layer, outerwear only		9.3	0.3	50	50	40	19 (only 2 of 3)	7-8	115	40
		22, 21	woven	12.3-12.5		40	35	30	---	4-7	--	30
10	55/35 polyester/rayon	single layer, outerwear only		5.9	4.6	50	60	50	9-11	3-5	65	50
		20, 19	knit	9.3-9.5		45	40	30	10-11	4-5	75	30
NOMEX T-456:												
17	95/5 Nomex/Kevlar	single layer, outerwear only		4.6	6.0	35	90	80	---	45-50	--	70
		20, 19	knit	8.0-8.2		45	50	35	---	4-7	--	35
		22, 21	woven	7.6-7.8		45	55	35	---	5-28	--	80

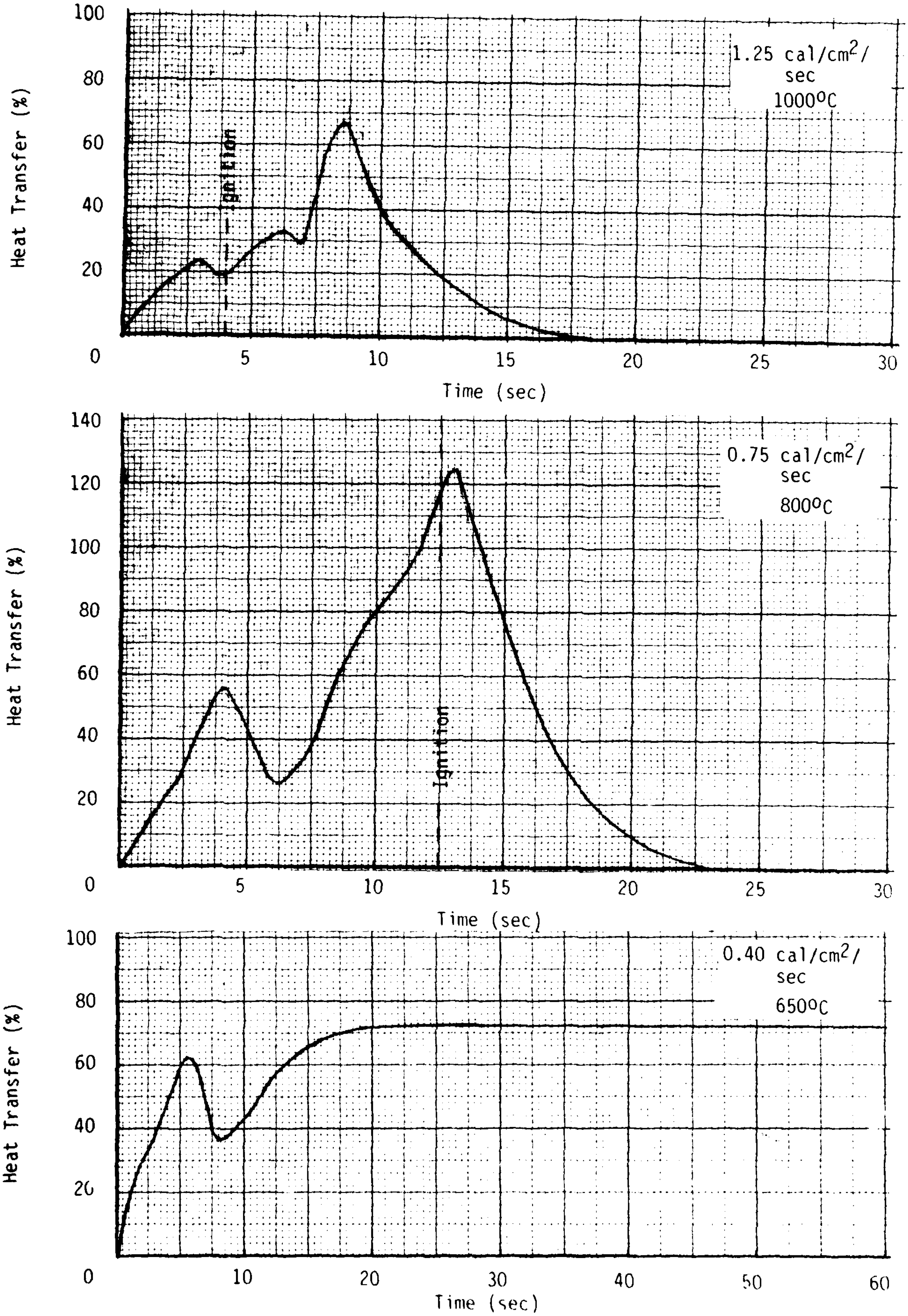


Figure 47. Typical Radiant Heat Transfer for Outerwear Fabric #16, 65/35 Polyester Cotton Blend

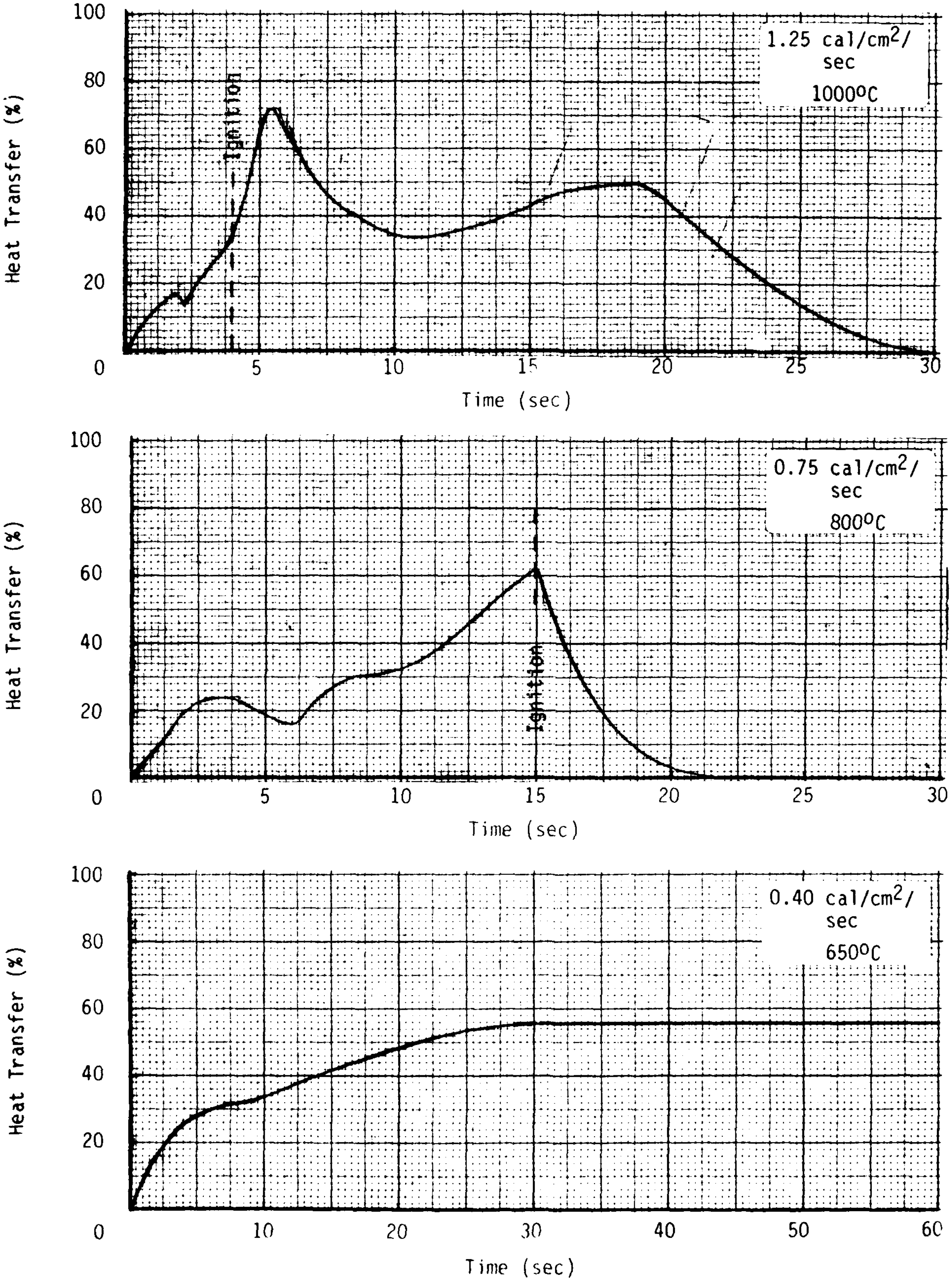


Figure 48. Typical Radiant Heat Transfer for Fabric Assembly - Outerwear Fabric #16, 65/35 Polyester/Cotton Blend, and Knit Underwear Fabric

The results of measurements of light transmission through single layers of the various fabrics are also included in Table 4. These values were determined using a light box equipped with a 75-watt incandescent lamp; the box is sealed except for a 2.4-inch diameter translucent window over which a fabric specimen may be mounted. Light intensities, both with or without a specimen in place, are measured in a darkened room with a sensitive photometer which is rigidly fixed 4 inches from the opening in the light box. The light transmission of each fabric is expressed as the percentage of the incident light which passes through the structure. The measured values of light transmission for the outerwear fabrics are generally less than 10% with the exception of the following lighter weight and/or lighter colored fabrics:

fabric 15, 65/35 polyester/cotton, 4.4 oz/sq yd, 15%
fabric 7, 50/50 polyester/cotton, 6.9 oz/sq yd, 24%
fabric 11, 50/50 polyester/cotton, 3.5 oz/sq yd, 27%.

The light transmission through single layers of both the white and lightweight underwear fabrics ranged between 30 and 40%. Light transmission through fabric assemblies was not determined but would obviously be less than through a single layer of outerwear fabric alone.

Comparison of the maximum heat transfer levels measured during the first 10 seconds of exposure with measured values of light transmission, summarized in Table 4, shows that even in those instances where ignition did not occur the level of heat transferred to the calorimeter is considerably greater than can be accounted for on the basis of transmitted energy alone. Furthermore, at no time during the first 10 seconds of exposure of the fabrics did a plateau occur in the response curves which corresponded in level to the percentage of light which could be transmitted through the fabric structure. However, for the more transmissable fabrics 15, 7, 11, 19, 20 21 and 22 mentioned above, a jog in the heat transfer response curve occurred within approximately 2-3 seconds of the start of exposure which roughly corresponded to their light transmission values - 20 to 40%, but such a level was generally also reached by the lighter, more opaque fabrics in this time period as well. Thus, it appears from examination of the individual calorimeter traces and the data in Table 4 that the level of heat transferred from irradiated fabrics or fabric assemblies is largely independent of both fabric pore size and fiber transmissability; <u>the sum of transmitted, reradiated and conducted heat seems to be about the same from fabric to fabric</u>. For those exposure conditions where ignition occurred, sufficient energy was generated from exothermic reactions within the fabric itself in some cases that the level of heat transferred to the underlying calorimeter was considerably higher than that incident on the outer fabric surface from the external source.

The effect of underwear fabric in combination with the various outerwear fabrics is, in general but not always, to decrease the amount of heat transferred to the underlying surface both within the first 10 seconds of exposure if no ignition occurs and after ignition, if it does. Ignition itself was not generally delayed by the presence of additional layers. In some cases ignition of fabric assemblies occurred where ignition of the single layer of outerwear fabric tested alone did not. There seems to be no distinct advantage of a particular underwear fabric <u>type</u> in lessening radiative heat transfer.

Protection from exposure to intense radiant heat does not depend significantly on the level of radiant energy which can be transmitted directly through the fabric structure of a garment. The heat transferred under such conditions is the sum of transmitted, reradiated and conducted energy. Reradiation and conduction from the inner surface of the hot fabric depends principally on the temperature of the fabric at a given time and the level of contact between the inner layers of the garment and the skin. Additional fabric layers between the outer layer and the skin serve to slow the rate of temperature rise of the garment as a whole because of the increased mass of the assembly, to decrease the amount of energy transmitted, and to retard temperature rise on the inner surface of the garment because of an increase in overall thickness. If the level of contact is good, the heat transfer mode will be primarily conductive; if there is less contact, reradiation will be the dominant mode of transfer in the tighter fabrics.

V. FLAME-IMPINGEMENT HEAT TRANSFER

A. Flame-Impingement Tester and Test Procedure

The statement of work governing the performance of the subject contract requires measurement of heat transfer through 17 outerwear fabrics and 48 outerwear/underwear fabric assemblies in a flame-impingement situation. Accordingly, our flame-impingment device, patterned after that of Alice Stoll of the Naval Air Development Center[10] was rebuilt with several new features to facilitate such testing. The device consists essentially of a Meker burner flame source, a specimen holder which includes a skin-simulant sensor, and a shuttering system for controlling the initiation and timing of exposure of the specimen to the flame. A diagram of the device is given in Figure 49, and photographs are presented in Figure 50.

The Meker burner, located 2.1 inches from the surface of the fabric during a test, causes a vertical propane flame calibrated to a total heat flux of 2.2 ± 0.1 cal/cm^2/sec to impinge perpendicularly on the surface of a horizontally mounted test specimen. This level of heat flux was chosen to conform to the value of heat flux generally accepted as average for a large fueled fire[2]. The flame is calibrated frequently by means of a water-cooled calorimeter and adjusted by altering the rate of gas flow at maximum air intake. During calibration the surface of the calorimeter is positioned in the flame at the same distance from the burner as is the fabric specimen during a test.

Prior to exposure a fabric swatch measuring about 4 inches in diameter is mounted in a special holder designed to provide uniform and reproducible clamping pressure, and a skin-simulant sensor is placed behind it in intimate contact. Figure 51 shows a fabric specimen mounted in the holder and the skin-simulant in its aluminum frame. The exposed portion of the specimen measures 2.0 inches in diameter; the diameter of the surface of the skin simulant is 1.5 inches and its thickness is 0.38 inches. The various components of the specimen holder are photographed separately in Figure 52 and shown diagramatically in cross-section in Figure 53 in their relative positions during exposure of the specimen to the flame. During mounting of the specimen, the mounting platform sits over a dummy skin simulant holder which protrudes slightly above its surface. The fabric specimen is centered over the dummy and a cover plate placed on it. Finally a knurled ring is used to secure the specimen in place. The specimen in the holder is then lifted off the dummy skin simulant, inverted, the real skin simulant in its holder inserted into place behind it, and the whole assembly secured to the movable carriage of the test device.

The skin simulant itself is produced from a special formulation of resins[11,12] and is designed to duplicate the optical and conductive properties of real skin. A fine-wire thermocouple embedded 500μ below the surface monitors heat flow through the specimen to the skin-simulant. During a test a continuous record of the temperature in the simulated skin is obtained as a function of duration of exposure.

(Text continued on page 87.)

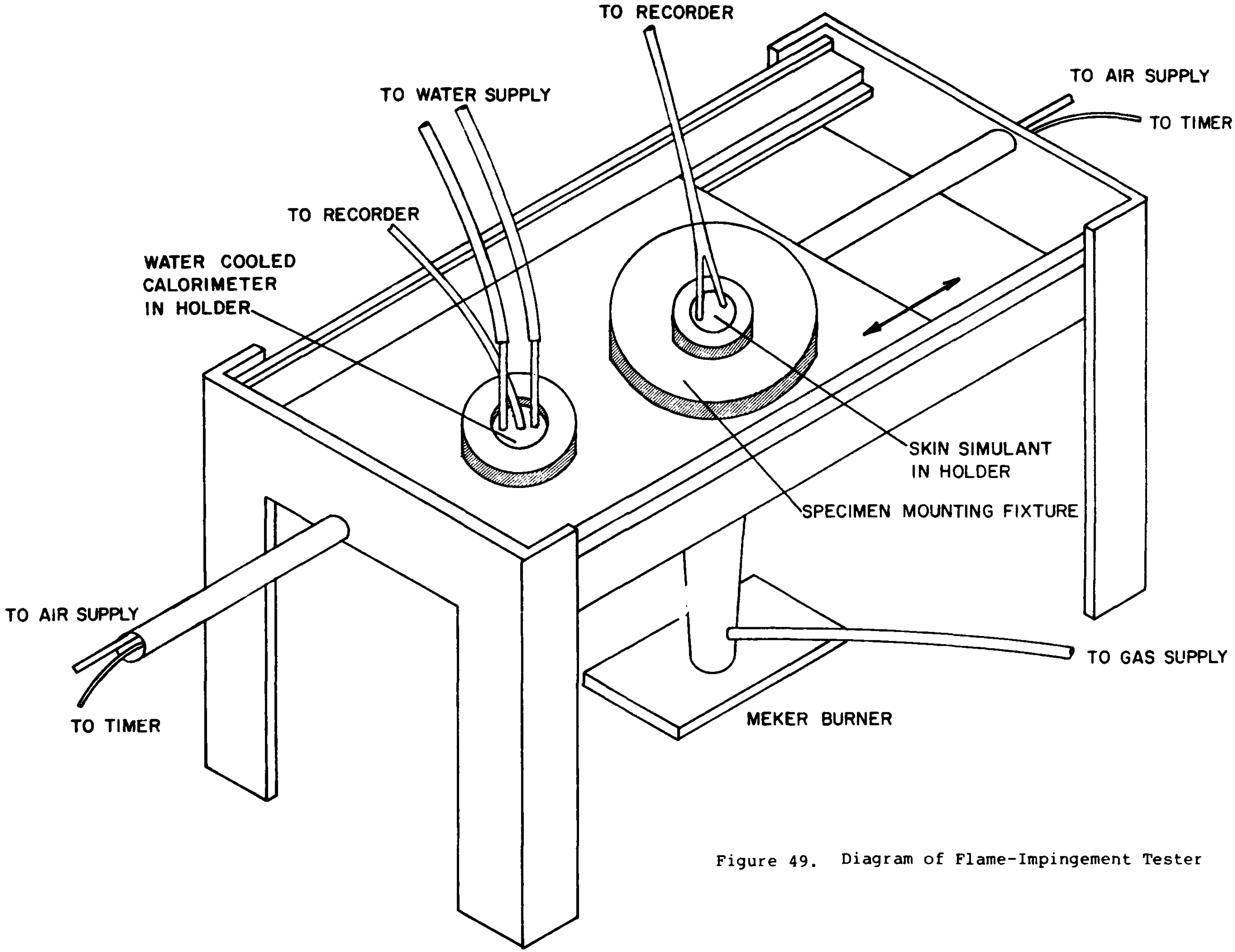
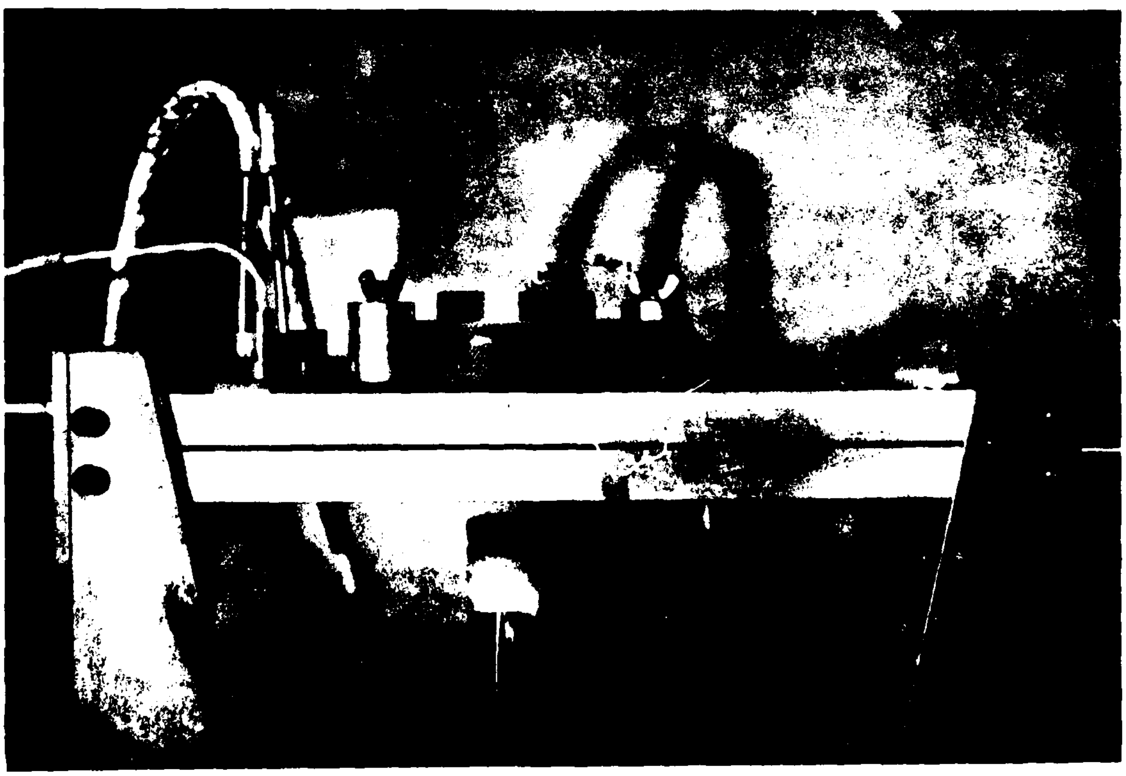


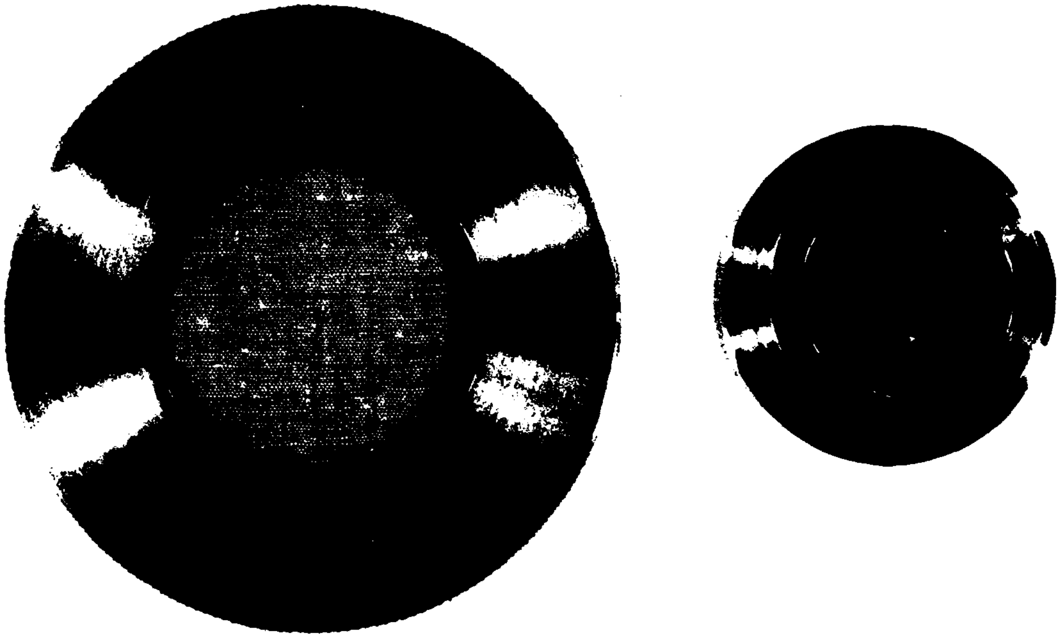
Figure 49. Diagram of Flame-Impingement Tester

(a)



(b)

Figure 50. Flame Impingement Tester: (a) Tester, Control Panel, Recorder
(b) Close-Up of Specimen Mounting Block Over Burner



Specimen in Place

Skin Simulant in Holder

Figure 51. Assembled Specimen Mounting Fixture and Skin-Simulant Holder

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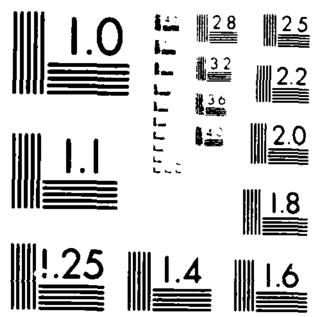

MICROCOPY RESOLUTION TEST CHART

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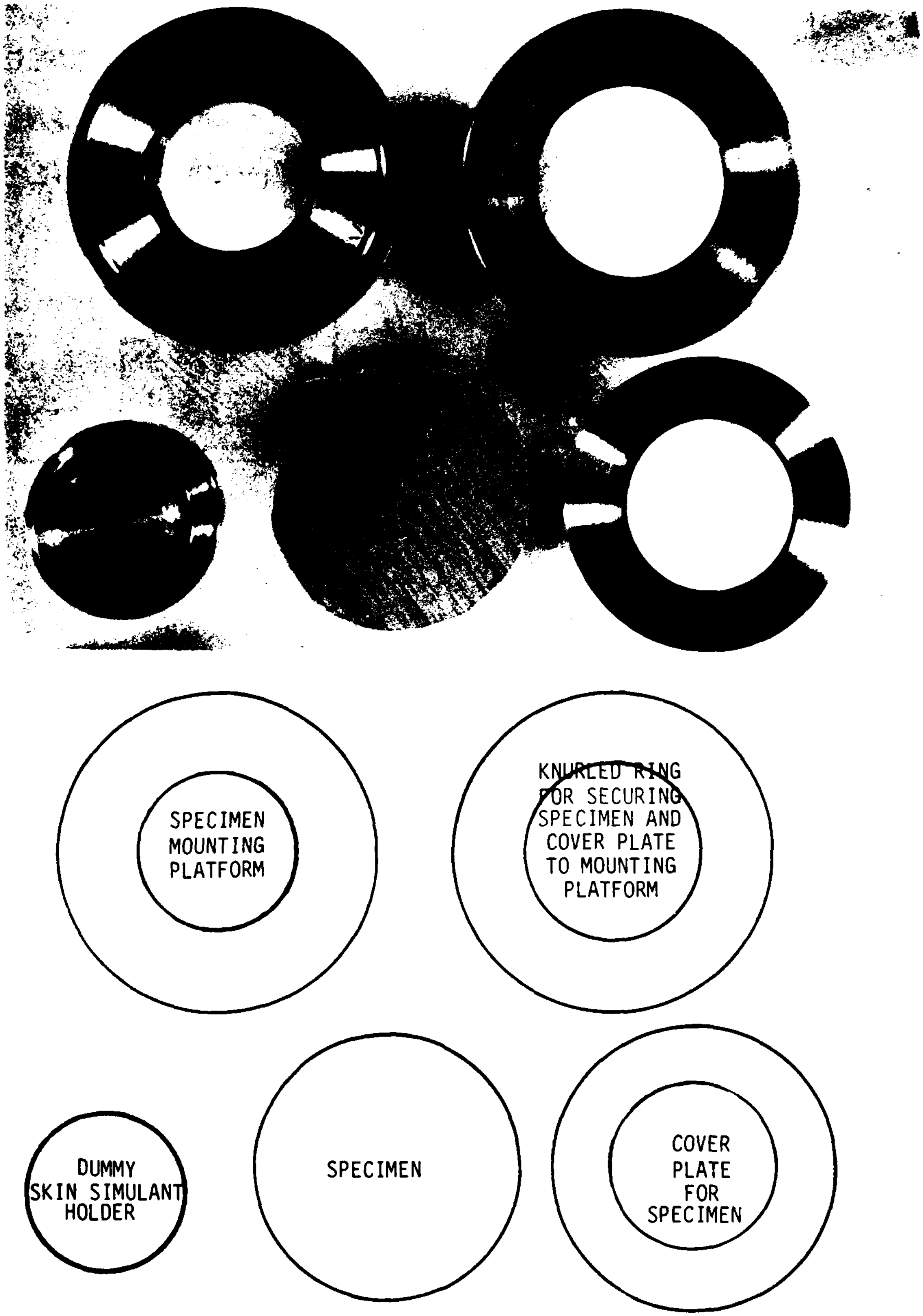


Figure 52. Specimen Mounting Fixture

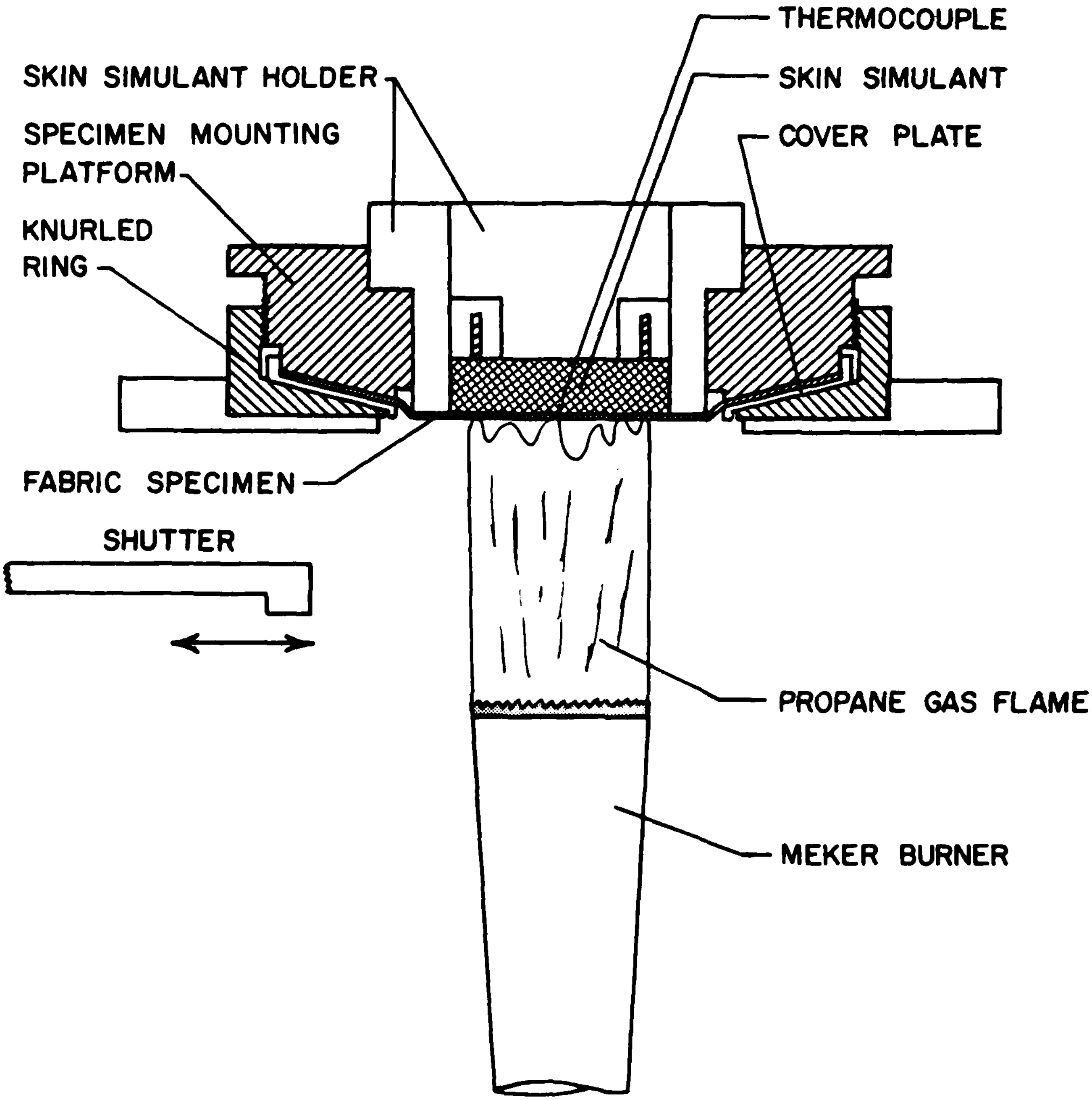


Figure 53. Cross-Sectional View of the Specimen Mounting Assembly and Skin-Simulant in Its Holder (actual size)

During a test, the flame is first lit and then activation of the air-operated and magnetically controlled shuttering system causes a precisely executed sequence of events to occur: the shutter, originally located beneath the mounted specimen off to one side of the flame, moves rapidly into position covering the flame; the carriage holding the specimen/skin-simulant assembly then snaps into position over the shutter and the shutter is virtually simultaneously withdrawn; a timed exposure regulated by an automatic clock begins as the shutter is withdrawn; at the conclusion of exposure the carriage holding the specimen moves out of the flame. The quick motion of the shuttering and carriage-control system allows precise timing of the exposure (within milliseconds) so that a square-wave heat pulse is experienced by the fabric specimen. Exposures of 3- and 6-seconds duration were carried out for each of the fabrics and fabric assemblies in the test series.

All of the testing reported herein was performed with the skin simulant in direct contact with the fabric specimen and therefore represents a worst-case situation. Provisions have been made in the specimen mounting system for maintaining precise spacing between fabric and skin simulant and between layers in fabric assemblies, but budgetary considerations prevented investigation of the effect of such controlled air gaps.

Typical skin-simulant temperature response curves are illustrated in Figure 54. These curves illustrate the rapid temperature rise during the period of actual flame-impingement, the attainment of maximum temperature a few seconds after cessation of exposure and the more gradual decrease of temperature as cooling proceeds.

Ignition of fabric specimens does not commonly occur during the flame-impingement test even though the outer surface of the fabric undoubtedly reaches temperatures sufficient to cause ignition. Specimens decompose, char and become ash but actual flaming of the specimen itself does not occur. This behavior has been observed even when the specimen is not backed up by a skin simulant and seems to be related to the phenomenon seen with old-time miners lamps (Davy lamp) in which a cotton or silk fabric mantle contained a flame without itself igniting. The higher viscosity of hot gases apparently prevents their penetration through a mesh structure of small pore size; there is undoubtedly also an oxygen deficiency of the gas flame on the specimen.

B. Test Results

The results of heat transfer measurements through various outerwear fabrics and outerwear/underwear fabric assemblies during flame impingement are summarized in Table 5. Both temperature rise in the skin simulant at 3- and 6-seconds and maximum temperature rise after 3- and 6-second exposures are reported. The entries to Table 5 are grouped according to outerwear fabric blend ratio and fabric weight with subgroups constituted of combinations of the particular outerwear fabric with each of the underwear fabrics of interest. Fabric assembly weights and thicknesses measured at two pressure levels are also included in the table. In general, three replicate specimens of each fabric type were tested at each condition. Individual test results are given in Appendix Table 4. A relatively low level of variation was observed between replicate specimens; considerable differences in the ability to retard heat transfer exist, however, between fabrics in the test series.

(Text continued on page 91.)

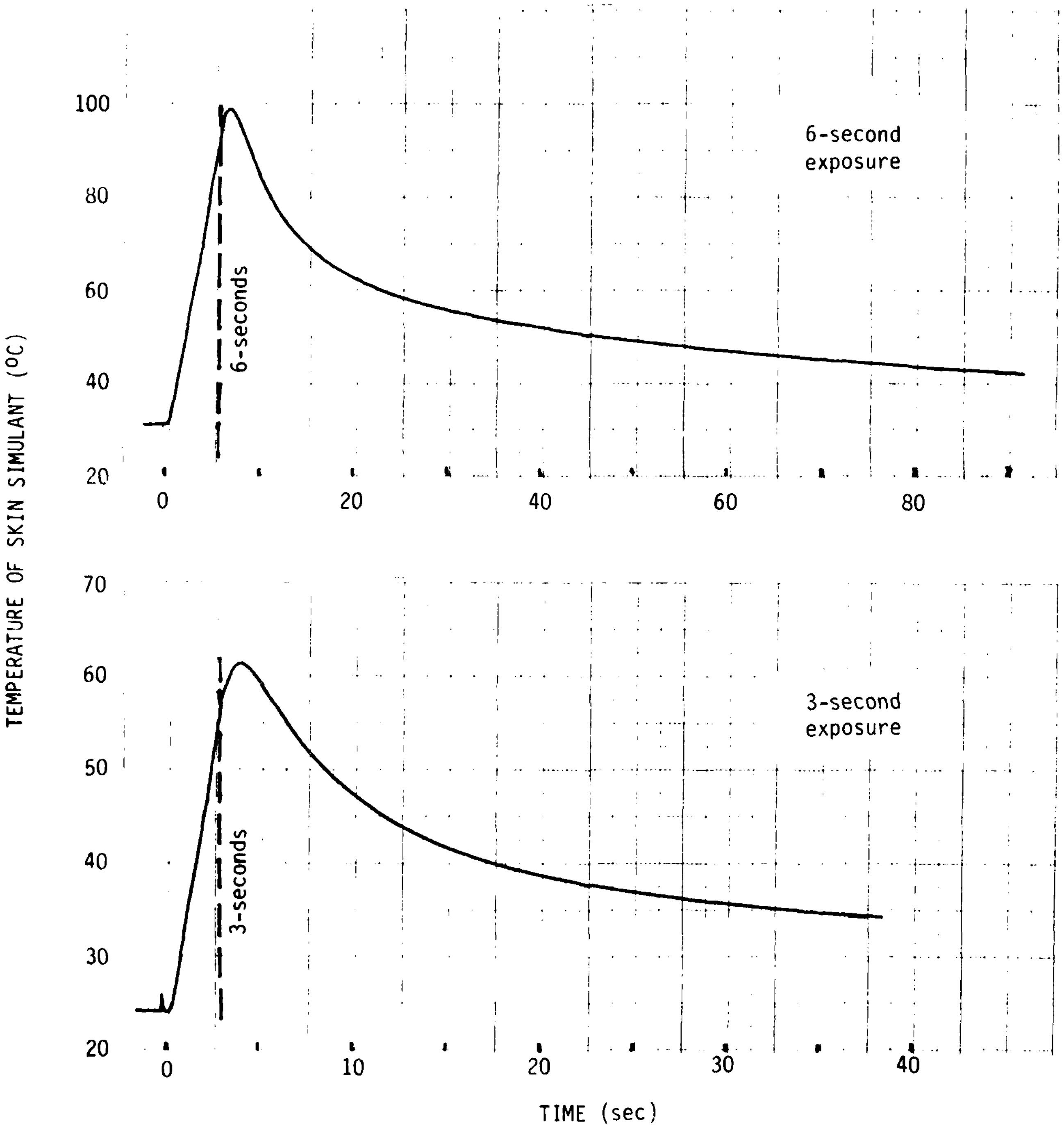


Figure 54. Typical Skin Simulant Response Curves - 2.2 cal/cm^2/sec (Nomex T-456)

Table 5. Average Temperature Rise in Skin Simulant and Estimate of Burn Injury Potential with Various Fabric Assemblies During Flame Impingement

Outerwear Fabric No.	Outerwear Blend Ratio	Underwear Fabric No.	Underwear Blend Ratio (poly/cotton)	Assembly Weight (oz/sq yd)	Assembly Thickness (cm) 0.63 psi	Assembly Thickness (cm) 0.035 psi	Temperature Rise (°C) at 3 sec	Temperature Rise (°C) at 6 sec	Maximum Temperature Rise (°C) 3 sec exp	Maximum Temperature Rise (°C) 6 sec exp	Burn Injury Index[1] 3 sec exp	Burn Injury Index[1] 6 sec exp
POLYESTER/COTTON BLENDS:												
13	100/0	--	--	6.0	0.064	0.074	50.6	101.0	55.8 melts	101.0	∞[2]	∞
		20	65/35	9.4	0.109	0.123	12.8	30.3	15.4	35.9	16	∞
		22	65/35	9.0	0.086	0.104	23.8	50.0	27.8	53.8	∞	∞
		19	0/100	9.6	0.112	0.124	13.6	36.5	17.0	37.7	10	∞
		21	0/100	9.2	0.086	0.104	21.7	51.7	25.6	53.5	∞	∞
9 (doubleknit)	100/0	--	--	6.0	0.089	0.094	46.7	97.9	49.9	101.3	∞	∞
		20	65/35	9.4	0.135	0.142	9.7	31.2	15.5	34.1	2.2	∞
		22	65/35	9.0	0.112	0.124	19.9	52.1	22.5	54.5	68	∞
		19	0/100	9.6	0.137	0.145	10.2	26.8	13.1	30.5	0.9	∞
		21	0/100	9.2	0.112	0.124	19.1	51.3	24.9	53.7	∞	∞
6	65/35	--	--	7.0	0.041	0.046	26.6	49.7	32.2	52.8	∞	∞
		22	65/35	10.0	0.064	0.076	17.0	36.6	22.6	40.8	∞	∞
		21	0/100	10.2	0.064	0.076	15.8	35.0	22.7	39.8	∞	∞
16	65/35	--	--	5.8	0.038	0.041	31.9	55.4	34.5	57.3	∞	∞
		20	65/35	9.2	0.084	0.089	11.4	25.4	19.2	30.2	12	∞
		22	65/35	8.8	0.061	0.071	15.1	34.2	21.6	41.0	∞	∞
		19	0/100	9.4	0.086	0.091	13.3	26.1	18.3	29.0	60	∞
		21	0/100	9.0	0.061	0.071	15.2	36.0	24.5	40.7	∞	∞
12	65/35	--	--	4.8	0.036	0.036	30.8	68.3	34.0	73.9	∞	∞
		20	65/35	8.2	0.081	0.084	11.2	27.1	20.1	28.6	20	∞
		19	0/100	8.4	0.079	0.086	12.3	27.3	18.4	30.2	81	∞
15	65/35	--	--	4.4	0.030	0.030	29.2	48.1	31.4	56.5	∞	∞
		20	65/35	7.8	0.076	0.079	10.6	27.7	20.6	28.9	44	∞
		19	0/100	8.0	0.079	0.081	11.4	29.5	17.1	30.8	89	∞
Single layer, underwear fabric only		20 (knit)	65/35	3.4	0.046	0.048	17.9	46.6	37.3	56.2	∞	∞
		22 (woven)	65/35	3.0	0.023	0.030	30.9	69.2	35.9	72.0	∞	∞
7	50/50	--	--	6.9	0.048	0.051	24.9	37.0	27.5	44.0	∞	∞
		22	65/35	9.9	0.071	0.081	15.6	36.3	22.9	41.7	367	∞
		21	0/100	10.1	0.071	0.081	17.0	36.7	23.5	42.8	221	∞
11	50/50	--	--	3.5	0.030	0.036	41.6	75.2	46.3	77.4	∞	∞
		20	65/35	6.9	0.076	0.084	13.1	30.7	21.0	32.9	117	∞
		19	0/100	7.1	0.079	0.086	13.7	33.0	19.7	36.1	78	∞
1	35/65	--	--	10.3	0.076	0.074	13.1	23.9	18.0	33.1	49	∞
		22	65/35	13.3	0.099	0.104	9.9	22.5	17.8	37.0	12	∞
		21	0/100	13.5	0.099	0.104	10.3	21.8	18.4	38.4	4.9	∞

[1] Temporal integral of burn injury rate curve for first 10 seconds of exposure.

[2] A burn injury index of ∞ means that the temperature rise at a depth of 80μ in the skin simulant is estimated to have exceeded 39.5°C.

Table 5. Average Temperature Rise in Skin Simulant and Estimate of Burn Injury Potential with Various Fabric Assemblies During Flame Impingement (cont)

Outerwear Fabric No.	Outerwear Blend Ratio	Underwear Fabric No.	Underwear Blend Ratio (poly/cotton)	Assembly Weight (oz/sq yd)	Assembly Thickness (cm) 0.63 psi	Assembly Thickness (cm) 0.035 psi	Temperature Rise (°C) at 3 sec	Temperature Rise (°C) at 6 sec	Maximum Temperature Rise (°C) 3 sec exp	Maximum Temperature Rise (°C) 6 sec exp	Burn Injury Index[1] 3 sec exp	Burn Injury Index[1] 6 sec exp
POLYESTER/COTTON BLENDS (cont):												
3	0/100	--	--	10.3	0.074	0.074	14.3	25.7	18.0	33.1	47	∞[2]
		22	65/35	13.3	0.097	0.104	12.1	22.3	15.4	34.8	10	∞
		21	0/100	13.5	0.097	0.104	11.9	23.7	16.6	31.2	10	∞
18	0/100 (FR treated)	--	--	6.9	0.046	0.053	21.1	51.5	26.6	52.5	∞	∞
		20	65/35	10.3	0.091	0.102	10.5	37.3	18.5	39.5	11	∞
		22	65/35	9.9	0.069	0.084	11.7	43.8	19.7	45.8	39	∞
		19	0/100	10.5	0.094	0.104	11.7	38.4	16.3	41.9	24	∞
		21	0/100	10.1	0.069	0.084	12.3	42.2	19.6	44.2	39	∞
Single layer, underwear fabric only		19 (knit)	0/100	3.6	0.048	0.051	24.5	42.2	29.8	44.7	∞	∞
		21 (woven)	0/100	3.2	0.023	0.030	31.7	79.4	35.3	81.3	∞	∞
POLYESTER/WOOL BLENDS:												
8	75/25	--	--	6.4	0.046	0.046	24.8	62.7	26.8	67.5	∞	∞
		20	65/35	9.8	0.091	0.094	9.9	24.2	17.8	28.6	10	∞
		22	65/35	9.4	0.069	0.076	14.7	40.9	24.6	42.4	215	∞
		19	0/100	10.0	0.094	0.097	10.8	23.9	16.9	29.3	8	∞
		21	0/100	9.6	0.069	0.076	14.7	41.6	23.7	47.3	144	∞
2	55/45	--	--	6.4	0.048	0.048	22.9	42.9	30.8	48.9	∞	∞
		22	65/35	9.4	0.071	0.078	15.6	33.2	24.8	41.5	∞	∞
		21	0/100	9.6	0.071	0.078	14.2	32.9	22.9	40.7	191	∞
14	0/100	--	--	8.4	0.104	0.109	12.3	26.0	15.5	28.6	3.8	∞
		20	65/35	11.8	0.150	0.157	8.5	16.1	11.8	18.6	0.1	47
		22	65/35	11.4	0.127	0.140	11.8	19.4	13.0	22.0	0.4	308
		19	0/100	12.0	0.152	0.160	8.0	16.1	11.8	18.3	0.1	61
		21	0/100	11.6	0.127	0.140	10.6	18.8	13.8	21.4	0.6	238
OTHER BLENDS:												
4	50/50 (nylon/cotton)	--	--	9.3	0.051	0.064	23.1	39.0	31.3	39.7	∞	∞
		22	65/35	12.3	0.074	0.094	11.9	23.2	19.1	25.7	10	∞
		21	0/100	12.5	0.074	0.094	9.7	17.8	15.1	26.0	3.9	∞
10	65/35 (polyester/ rayon)	--	--	5.9	0.043	0.046	25.2	47.5	30.3	55.9	∞	∞
		20	65/35	9.3	0.089	0.094	11.7	24.8	17.6	32.7	19	∞
		19	0/100	9.5	0.091	0.097	13.9	27.7	19.1	38.3	38	∞
NOMEX T456:												
17	95/5 (Nomex/Kevlar)	--	--	4.6	0.038	0.048	29.1	63.2	35.5	68.3	∞	∞
		20	65/35	8.0	0.084	0.097	17.4	39.5	26.0	44.6	∞	∞
		22	65/35	7.6	0.061	0.079	21.3	52.9	31.7	56.2	∞	∞
		19	0/100	8.2	0.086	0.099	14.9	36.0	23.5	42.5	148	∞
		21	0/100	7.8	0.061	0.079	20.4	51.0	29.5	52.3	∞	∞

[1] Temporal integral of burn injury rate curve for first 10 seconds of exposure.

[2] A burn injury index of ∞ means that the temperature rise at a depth of 80μ in the skin simulant is estimated to have exceeded 39.5°C.

In order to be able to make general statements concerning the relative performance of the various fabric types and underwear/outerwear combinations, which vary through a wide range of weights and thicknesses, it is helpful to examine graphically the nature of the variation of temperature rise with weight and thickness both for the test group as a whole and also for various subgroupings. Accordingly, the maximum temperature rise values have been plotted as a function of assembly weight in Figures 55a to 55d and of assembly thickness in Figures 56a to 56d: Figures 55a & c and 56a & c are given for the 3-second exposures and Figures 55b & d and 56b & d, for the 6-second exposures. In Figures 55a & b and 56a & b, the data is divided into subgroups according to the underwear fabric used in the assembly, and according to material type, either all cotton or all 65/35 polyester/cotton combinations, in Figures 55c & d and 56c & d (the only two material types represented by the four underwear fabrics in the test group are 100% cotton and 65/35 polyester/cotton). The relationship between weight and thickness of the assemblies is similarly graphed in Figures 57a & b.

A least-squares analysis was performed on the entire set of temperature rise/assembly weight data from which the best-fit regression line representing the behavior of the test assemblies as a whole was determined. The appropriate regression lines for the 3-second and 6-second exposures are superimposed on the data plotted in Figures 55a-d; correlation coefficients of -0.81 and -0.73 were calculated for the 3- and 6-second exposures respectively, a somewhat looser grouping of data being evident for the 6-second exposure. Linear regression analysis of the temperature rise/thickness data did not seem appropriate on examination of the data-point groupings in Figure 56; polynomial regression curves of order 2 and 3 were calculated but neither seemed to represent the general trend of the data particularly well. Consequently, a visually estimated best-fit curve was superimposed on the temperature rise/thickness data given in Figure 56. A best-fit line constrained to pass through the origin was also determined for the experimental relationship between weight and thickness; the correlation coefficient in this case was 0.69.

Examination of the distribution of points about the regression lines in Figures 55a & b and about the estimated curve in Figures 56a & b leads to the following observations:

1. On an equal weight basis the underwear/outerwear assemblies containing the knit underwear fabrics, 19 and 20 perform better, in general, (lower temperature rise) than those fabric combinations containing the woven underwear fabrics 21 and 22.

2. On an equal thickness basis there is no perceived advantage to one particular underwear type.

These observations suggest that some combination of the factors of weight and thickness such as assembly density may be an important characteristic of the fabric assemblies controlling the rate of heat flow; however, correlation of temperature rise with density was found to be negligibly low: on the order of 0.25 to 0.30. The distribution of points in Figure 57a indicates that those fabric assemblies containing knit underwear fabrics 19 and 20 are, in general, thicker than average for a given weight, or less dense (points to the right of the regression line), while those containing woven underwear fabrics 21 and 22 are thinner than average at a given weight, or more dense (points to the left

(Text continued on page 102.)

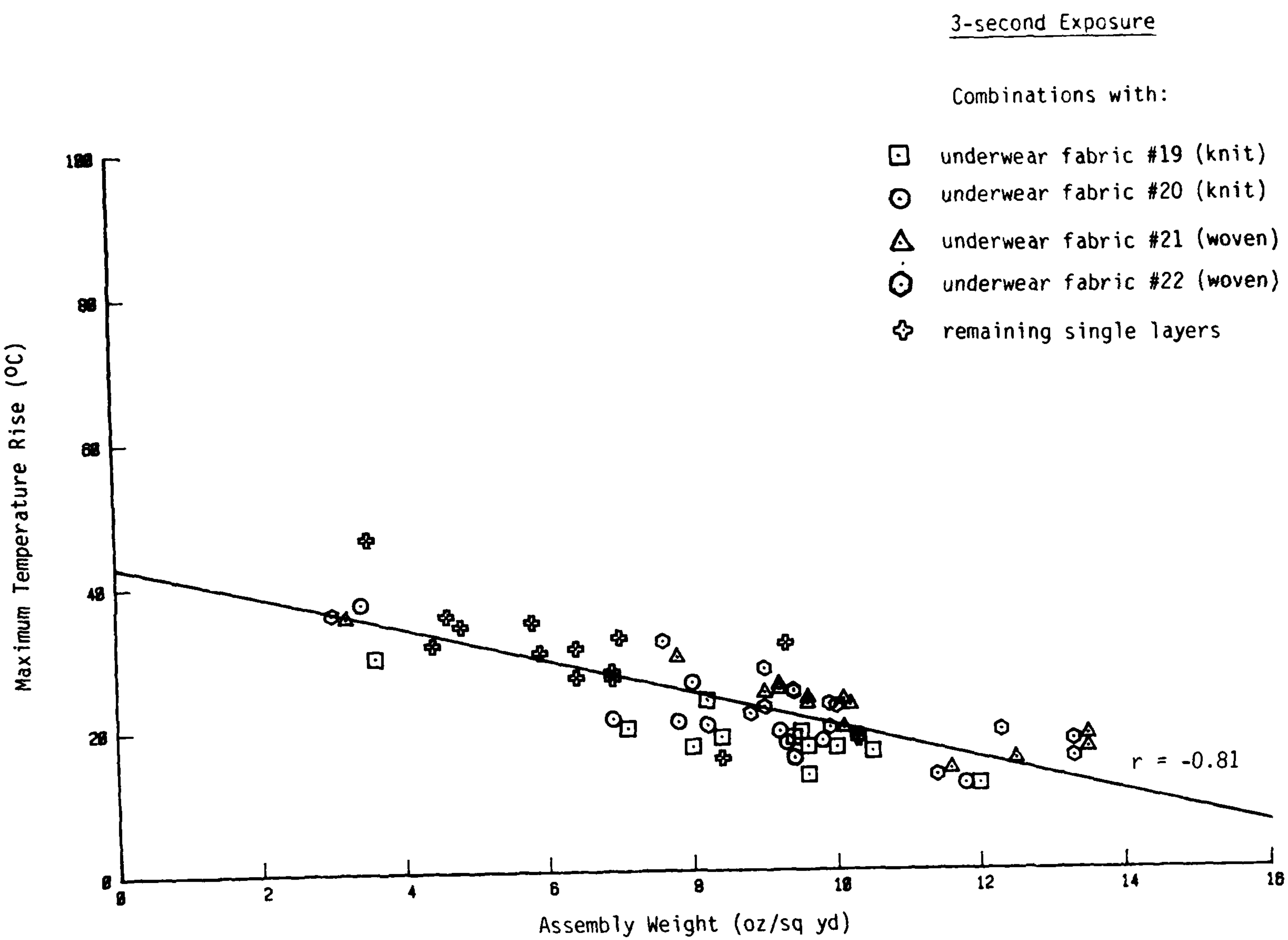


Figure 55a. Variation of Maximum Temperature Rise in Skin Simulant with Assembly Weight (Flame, 2.2 cal/cm^2/sec)

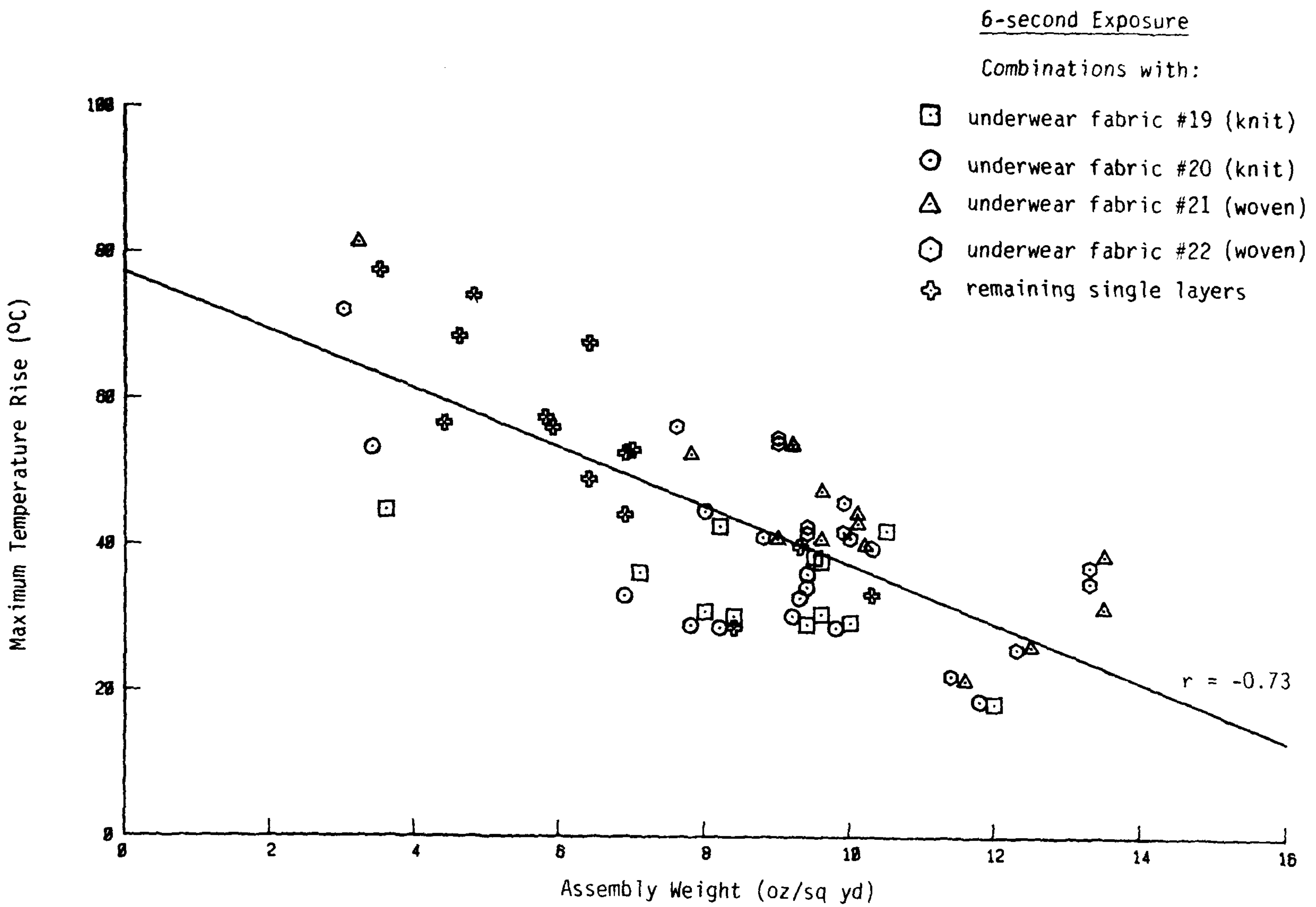


Figure 55b. Variation of Maximum Temperature Rise in Skin Simulant with Assembly Weight (Flame, 2.2 cal/cm^2/sec)

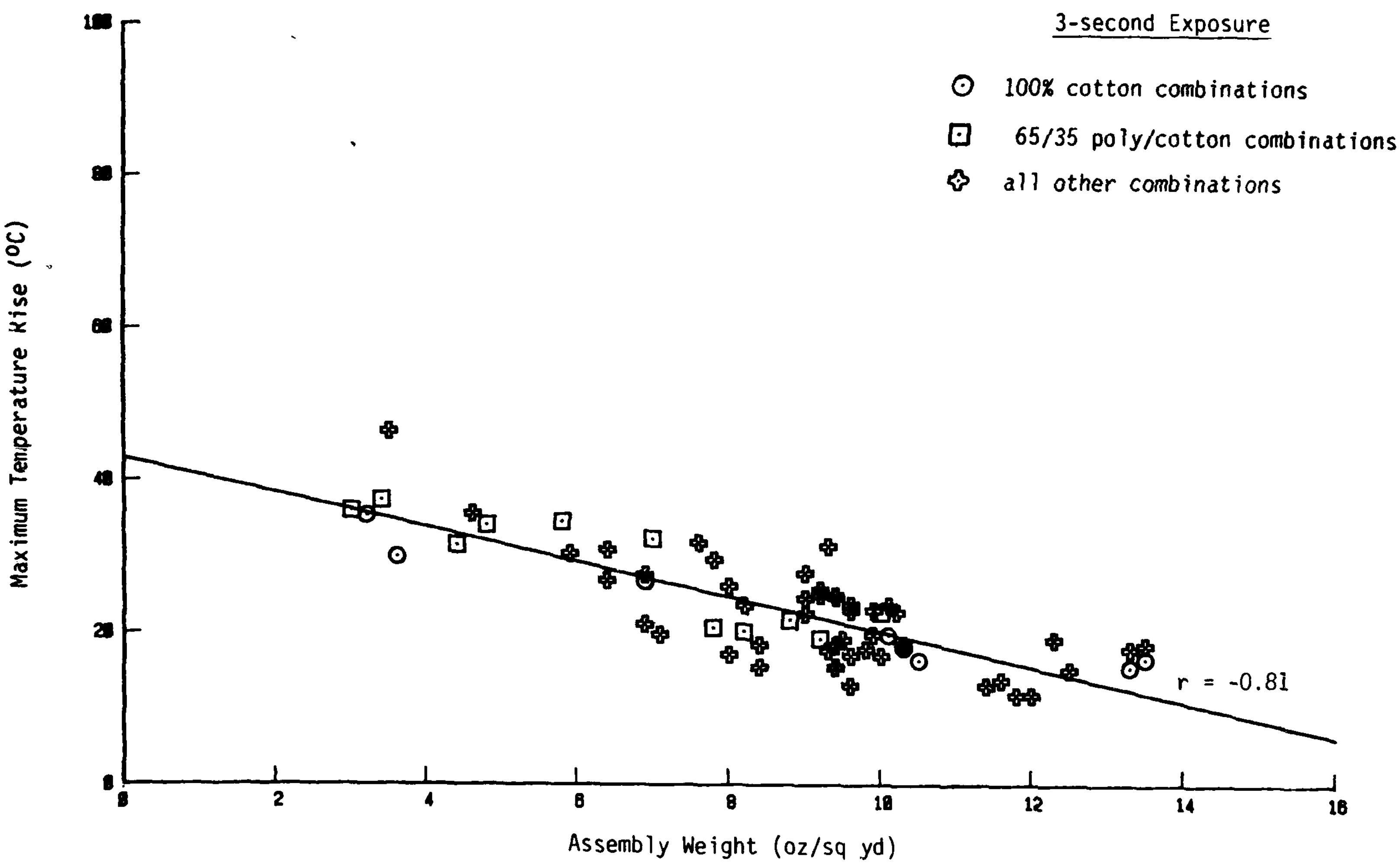


Figure 55c. Variation of Maximum Temperature Rise in Skin Simulant with Assembly Weight (Flame, 2.2 $cal/cm^2/sec$)

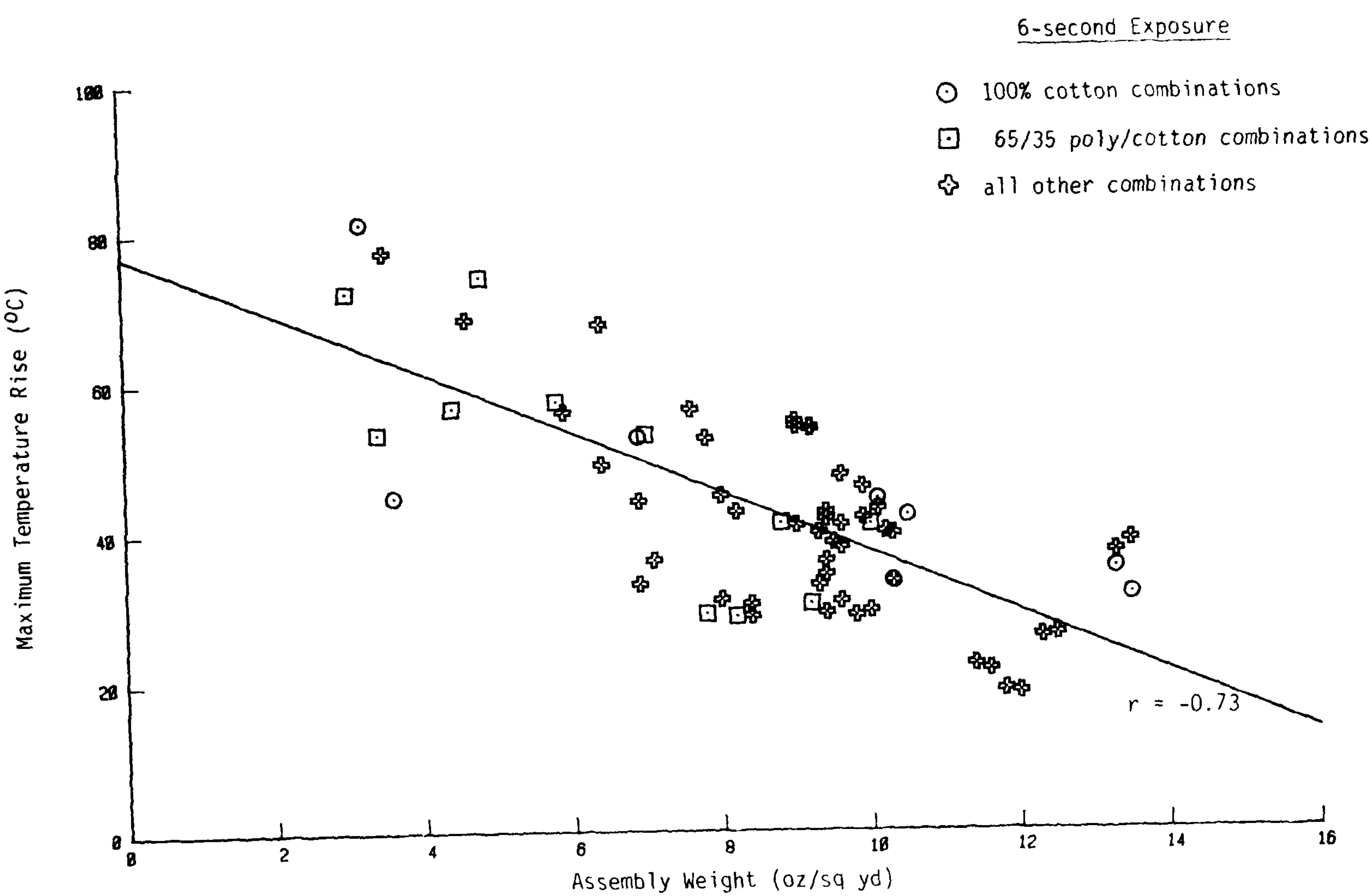


Figure 55d. Variation of Maximum Temperature Rise in Skin Simulant with Assembly Weight (Flame, 2.2 cal/cm^2/sec)

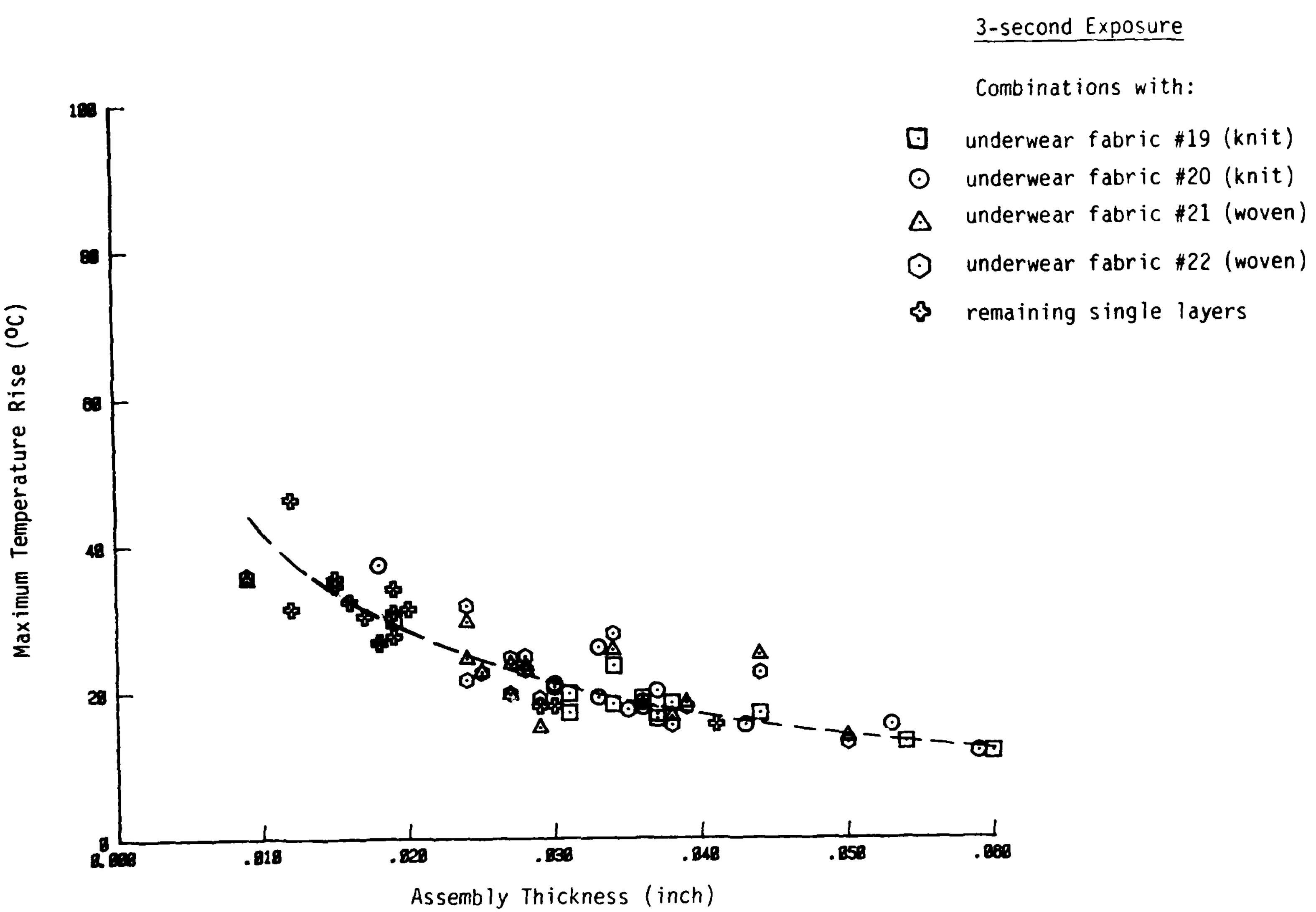


Figure 56a. Variation of Maximum Temperature Rise in Skin Simulant with Assembly Thickness (Flame, 2.2 cal/cm^2/sec)

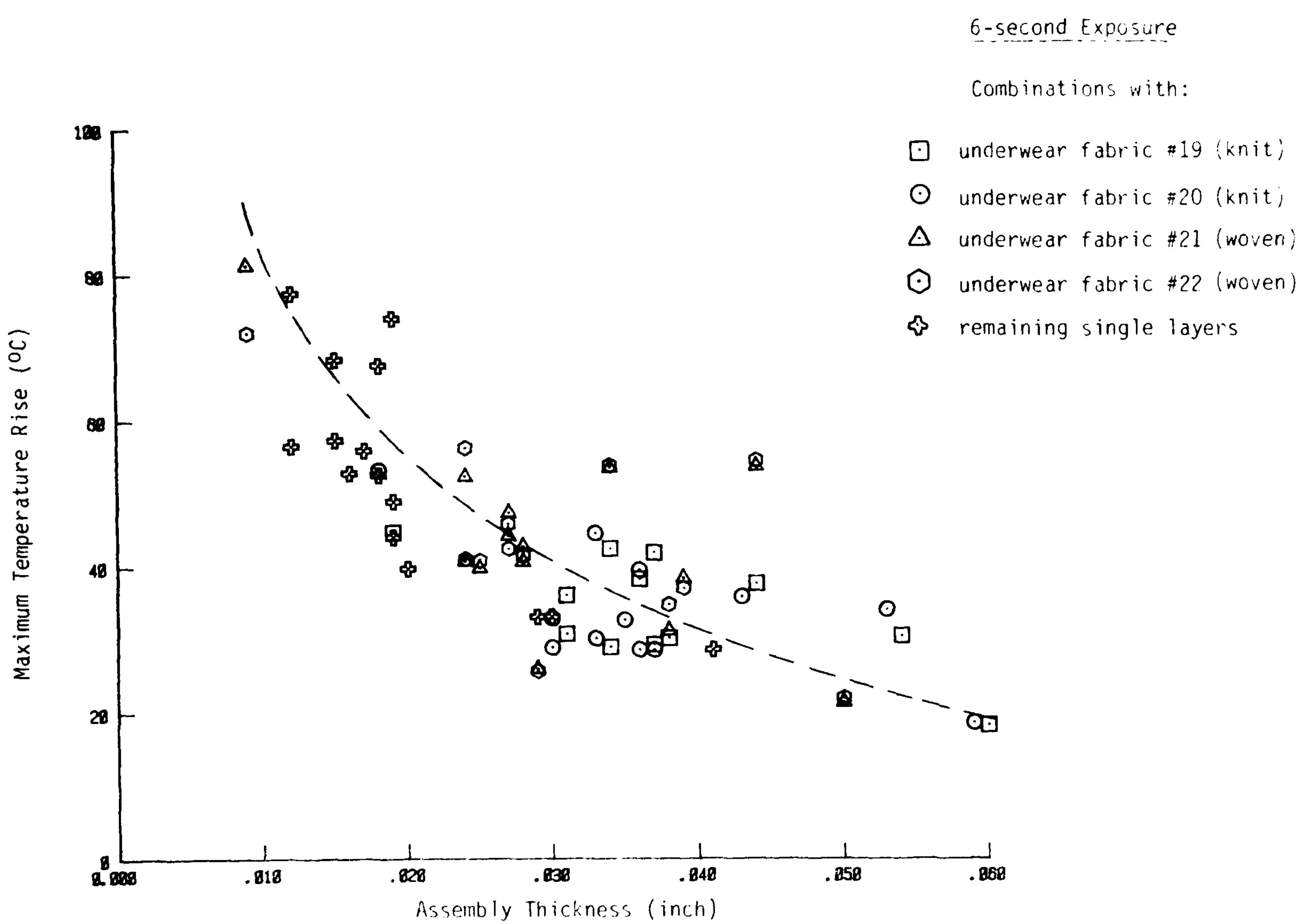


Figure 56b. Variation of Maximum Temperature Rise in Skin Simulant with Assembly Thickness (Flame, 2.2 cal/cm^2/sec)

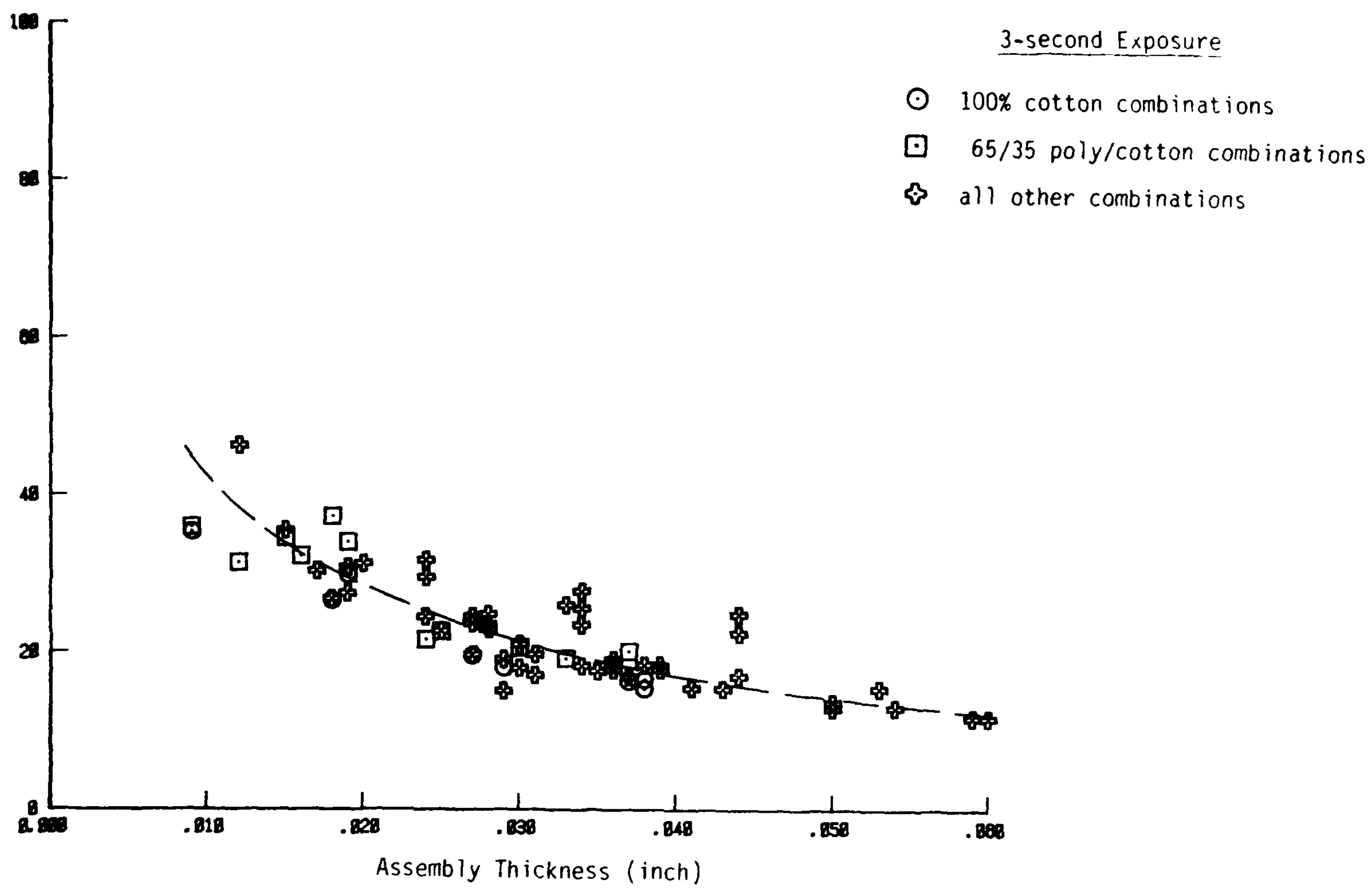


Figure 56c. Variation of Maximum Temperature Rise in Skin Simulant with Assembly Thickness (Flame, 2.2 cal/cm^2/sec)

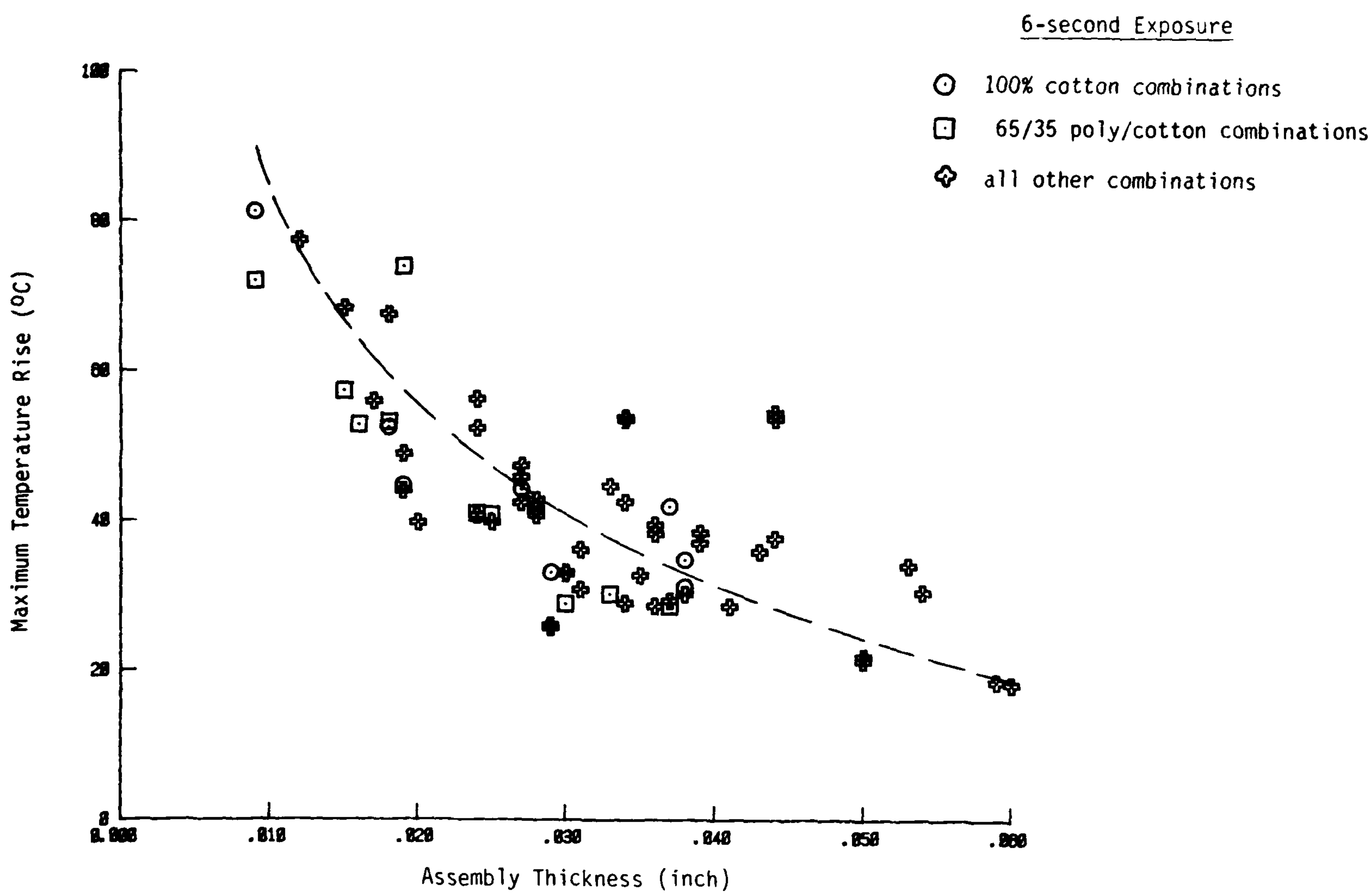


Figure 56d. Variation of Maximum Temperature Rise in Skin Simulant with Assembly Thickness (Flame, 2.2 cal/cm^2/sec)

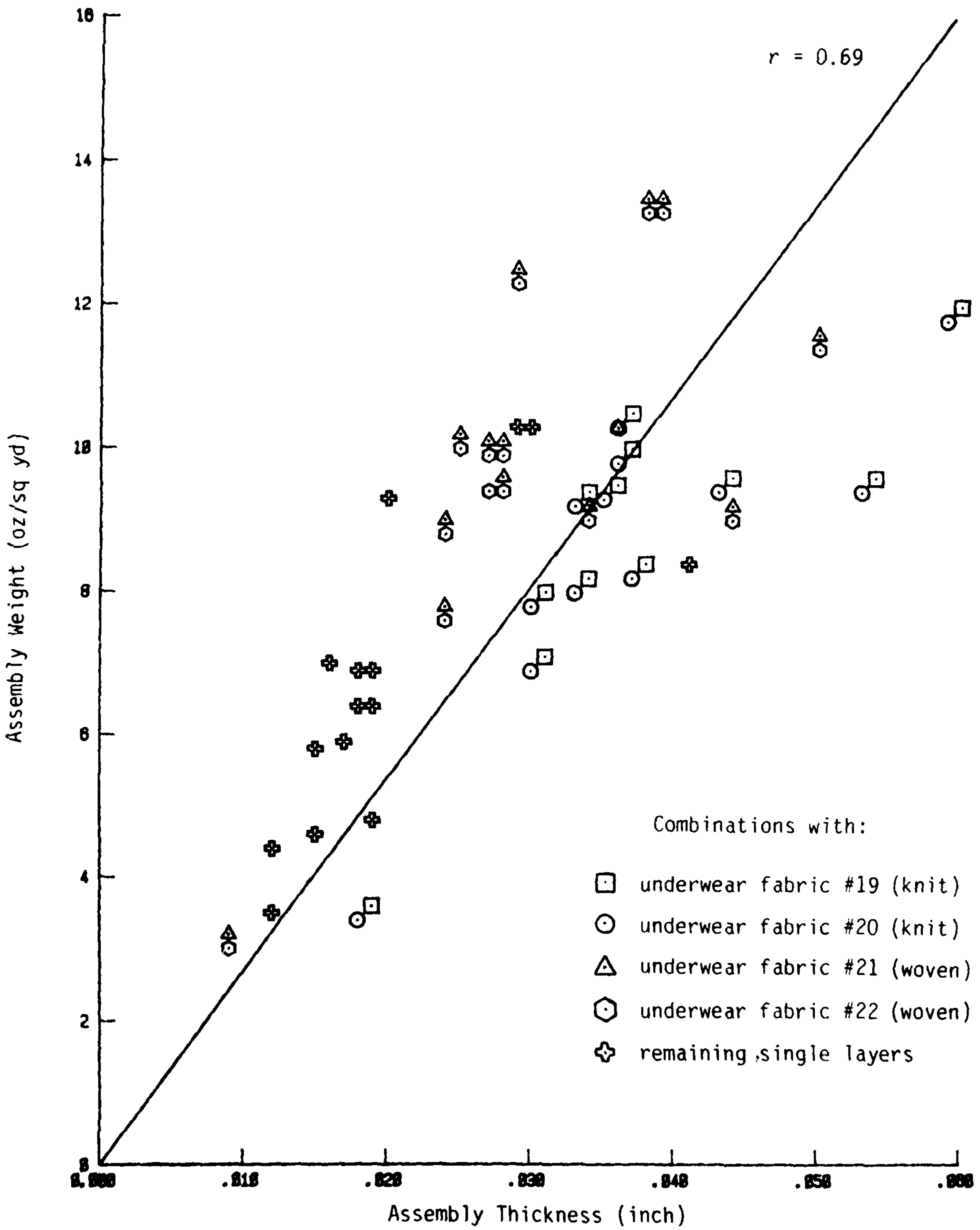


Figure 57a. Variation of Assembly Weight with Thickness

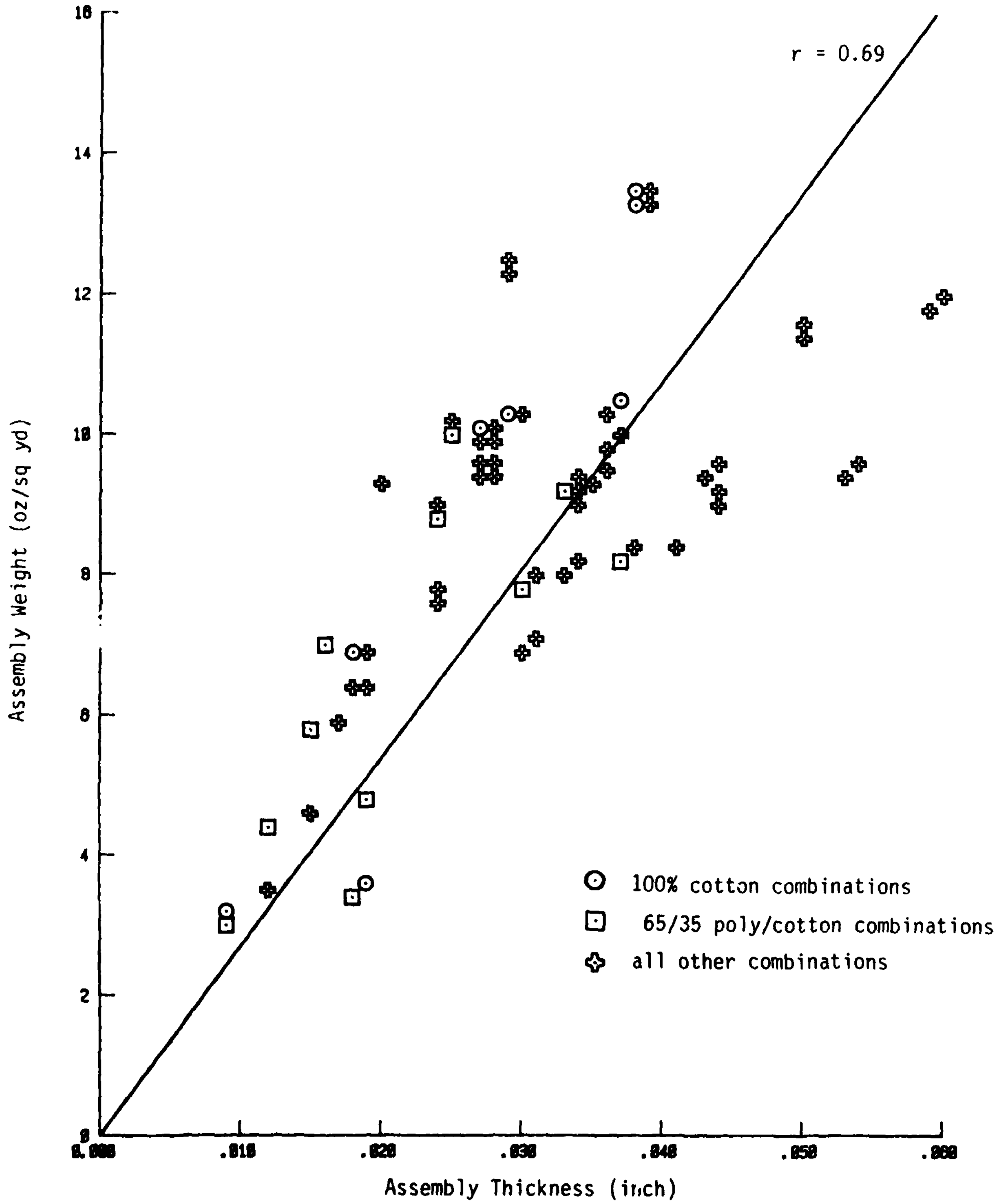


Figure 57b. Variation of Assembly Weight with Thickness

of the regression line); this seems to be a reasonable explanation for the contrast in performance on a weight basis between assemblies containing the thicker knit underwear fabrics and the thinner woven materials. By the same reasoning, however, fabrics of equal thickness which are heavier than average should perform better than those that are lighter; that is, when temperature rise is plotted against thickness one would expect from the data-point distribution of Figure 57a that heavier-for-their-thickness (more dense) assemblies containing woven underwear fabrics 21 and 22 (points above the regression line) would perform better than the lighter-for-their-thickness (less dense) combinations including knit underwear fabrics 19 and 20 (points below the regression line). Since the latter effect is not observed to any great extent in Figures 56a & b, it seems reasonable to conclude that fabric thickness is the primary factor affecting temperature rise during flame-impingement. The good correlation between fabric assembly weight and temperature rise in the skin simulant would seem to result principally from the correlation between weight and thickness.

Subgrouping of the temperature rise/weight data according to material type, whether all cotton or all 65/35 polyester/cotton assemblies (including single layers) in Figures 56c & d shows that on an equal thickness basis, the all cotton fabric assemblies show slightly lower than average temperature rises for 3-second exposures, Figure 56c, while the 65/35 polyester/cotton blends perform better, in general, in the 6-second exposures, Figure 56d. Because these two identifiable assembly groups lie generally above the regression line in Figure 57b, both materials would be expected to perform average or slightly better than average on an equal thickness basis. Other factors such as the high initial specific heat of cotton, which results from large amounts of sorbed water and the high specific heat of polyester as melting occurs, are also undoubtedly influencing the relative behavior of these materials at the different exposure times.

On a more individual basis we see from Table 5 in conjunction with Figures 55 and 56 that:

1. Exposure of single layers of 100% polyester fabrics results in exceptionally high temperature increases because the fabric melts through during testing and exposes the skin simulant directly to the flame; outerwear/underwear combinations involving the 100% polyester outerwear fabrics 9 and 13 and the woven underwear fabrics 21 and 22 also show higher temperature rises than the norm for fabrics of the same thickness.

2. All combinations involving the all wool fabric 14 offer superior performance on an equal weight basis because the wool fabric is considerably thicker for a given weight than the norm.

3. Nomex/Kevlar outerwear fabric 17 offers no particular heat transfer advantage.

It is obvious from the foregoing discussion that the heat transfer characteristics of the fabric asemblies in the test group can be largely understood in terms of the maximum temperature rise measured in the skin simulant in relation to assembly thickness. Other fabric properties such as melting behavior and material specific heat also play a role in the ultimate temperature achieved with a particular fabric or fabric assembly.

C. Burn Injury Potential

As the result of the pioneering work of several investigators[13-17], it has been established that the lower limit of temperature injurious to the skin is about 44°C. Above this temperature skin damage, possibly leading to blister formation, begins to accumulate. Blisters form at the basal layer of the skin at a depth of 80 to 100 microns below the surface, and it is the temperature at this depth which determines the level of damage. Burn injury proceeds all of the time that the temperature of the basal layer is above 44°C at a rate which increases logarithmically with increasing temperature above this level. At tissue temperatures above 72°C destruction of the skin occurs virtually instantaneously. Between these two temperature limits, the total extent of burn injury depends on the entire temperature history of the skin during exposure.

Stoll[16] details a method by which information concerning skin temperature as a function of time may be converted to burn injury rate vs. time curves using tissue damage rate data which she has established. According to her system if the temporal integral of the resulting damage rate vs. time curve exceeds unity over the period of time during which skin temperature is above 44°C (including both heating and cooling periods), the exposure will generally result in blister formation, or a second-degree burn; below the level of unity, a blister does not form; above it, the extent of burn injury is more severe but is not differentiated in terms of discrete stages of tissue damage.

We have attempted to use Stoll's system of determining the extent of burn injury during high-temperature exposure to evaluate the degree of protection offered by the various fabrics and fabric assemblies during flame impingement. The difficulty we have encountered with Stoll's method is that her tissue damage rate data is specific to the temperature at the basal layer of the skin, which she takes to be 80μ, while the temperatures recorded in the skin-simulant sensor during the flame-impingement tests are measured at a depth of 500μ. (The thermocouple cannot be placed closer to the surface of the skin simulant because the thermocouple bead approaches 80μ in diameter and erratic readings would result if it were not embedded at a greater distance from the surface). In her summary paper, Stoll includes a revision of Griffith & Horton's[18] heat flow equation (Eq 1, Ref. 16) which allows calculation of temperature rise U_2 in a two-layer assembly as a function of: thickness of the covering layer (fabric layer); depth in the second layer (skin or skin-simulant); elapsed time; and absorbed heat flux. The two layers are assumed to be in perfect contact. Their individual thermal properties, namely thermal conductivity and volumetric specific heat, must also be used in this calculation. We have verified that this equation reduces properly to the case of heat flow in a single layer in the limiting case where the thickness of the covering layer becomes vanishingly small[19].

We have programmed Stoll's equation for numerical solution by computer so that theoretical values of temperature rise in the skin simulant could be obtained at both the 80 and 500μ depths for a range of fabric properties; the purpose of these calculations was to obtain a means of converting temperatures measured at a depth of 500μ to the corresponding temperature at a depth of 80μ. For these calculations thermal properties of the skin simulant layer were taken from the literature on these materials; volumetric specific heat, 0.65 cal/^{o}C/cm^3, thermal conductivity, 1.31×10^{-3} cal/sec/^{o}C/cm[12]. In the absence of measured values of specific heat and thermal conductivity for the fabrics of interest, a range of values were used in the calculations; these values were 0.05, 0.10, 0.15, 0.20, 0.25 and 0.30 cal/^{o}C/cm^3 for the volumetric specific heats and 0.6, 0.8, 1.0, 1.2, 1.4 and 1.6×10^{-4} cal/sec/^{o}C/cm for thermal conductivities. The values of volumetric specific heat (density times specific heat) given above were chosen to cover the range appropriate to the measured values of density of the fabrics (weight divided by thickness in appropriate units), which varied between 0.2 and 0.6 gms/cm^3, and literature values of the specific heat of similar fabrics at temperatures between 50^{o}C and 250^{o}C, which spanned the range between 0.25 and 0.60 cal/g/^{o}C[20]. Published values of the thermal conductivity of similar fabrics generally lie between 0.6×10^{-4} and 1.6×10^{-4} cal/sec/^{o}C/cm[20,21].

The computer calculations using Stoll's equation provided us with theoretical values of temperature rise in the skin simulant at depths of both 80 and 500μ for quarter-second intervals during continuous exposure of layers of different thicknesses to a square-wave heat pulse of 6-seconds duration. Stoll's analysis, unfortunately, <u>does not apply after termination of the heat pulse</u> so that the maximum temperature reached in the skin-simulant cannot be estimated theoretically from her equation as it stands. Typical examples of the results of our calculations for a range of thicknesses of the covering layer and for specific assumed values of specific heat and thermal conductivity for this layer are graphed in Figure 58. This figure shows the variation in theoretical temperature rise at a depth of 80μ in the skin simulant layer with temperature rise at a depth of 500μ for the two extremes of heat flow covered by the range of fabric parameters assumed: maximum heat flow which occurs with minimum volumetric specific heat S_1 and maximum thermal conductivity k_1 of the covering layer; and minimum heat flow which occurs for the opposite pairing of values - maximum specific heat and minimum thermal conductivity. These two sets of curves in Figure 58 serve to illustrate the large effect thickness of the covering layer plays in determining temperature rise at the 80μ depth as a function of a given temperature rise at a depth of 500μ. For a temperature rise of 10^{o}C at a depth of 500μ, the temperature rise at 80μ ranges between 26^{o}C for a 0.16 cm thick fabric to greater than 45^{o}C for a 0.01 cm thick fabric under the conditions of maximum heat flow; similarly, for conditions of minimum heat flow, at a temperature rise of 10^{o}C at 500μ, the temperature rise at 80μ would be 22^{o} for a fabric thickness of 0.06 cm and 43^{o}C for a fabric thickness of 0.01 cm (a temperature increase of 10^{o}C at 500μ is not achieved with fabric thickness greater than 0.06 cm during a 6-second exposure under conditions of minimum heat flow). Obviously, the thickness of the covering layer has a profound effect on the temperature achieved at a depth of 80μ in the skin simulant as determined by the temperature at 500μ. The effect of the fabric thermal properties in determining temperature correspondence is also significant but not nearly as large as the effect of thickness of the covering layer. <u>A single-valued function for conversion of temperature from one depth to the other does not exist</u>.

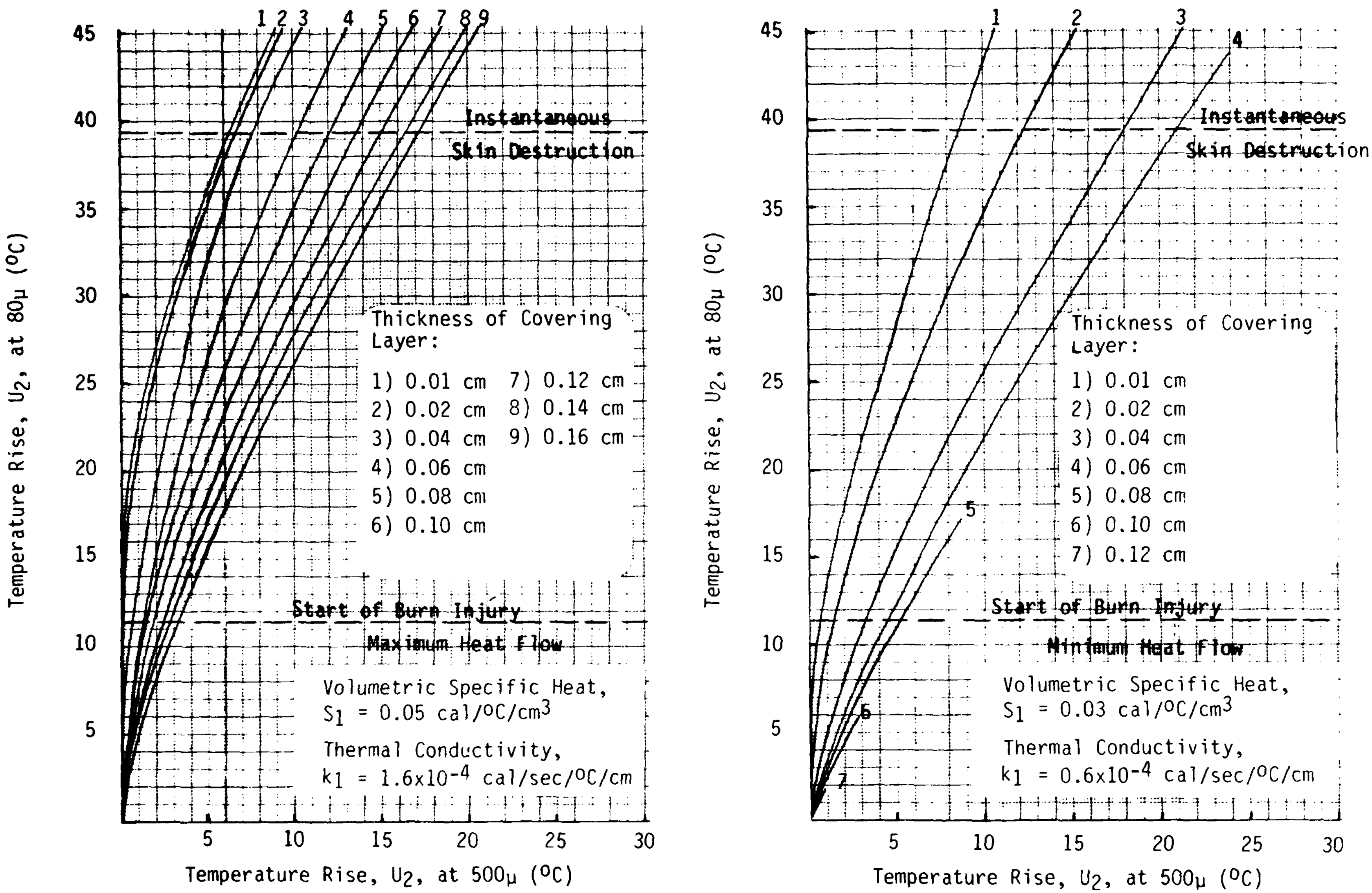


Figure 58. Theoretical Temperature Rise in the Skin Simulant During Flame Impingement. Maximum Range for Fabric Parameters Used (2.2 cal/cm^2/sec, 6-second exposure).

In an attempt to include the effect of cessation of the heat pulse in the theoretical calculations of heat flow, we programmed the heat-flow equation for the occurrence of a negative square-wave heat pulse of the same magnitude as the initial positive pulse at the 3- and 6-second exposure times but found that this method of accounting for termination of impinging heat flux vastly overestimated the actual maximum temperatures determined experimentally. The reason for this seems to be that the equations model only uni-directional heat flow from the surface of the fabric to the interior of the skin simulant whereas after actual flame-impingement ceases, more rapid cooling at the site of the thermocouple results not only from heat flow to the cooler interior of the skin simulant but also from flow back along the path of the initial advancing heat wave to the fabric surface where it is also dissipated. There is a need to incorporate properly the effect of cessation of the heat pulse in the theoretical equations of heat flow given by Stoll, but more sophisticated attempts to do so on our part were beyond the scope of this contract.

Furthermore, we found that the theoretical estimates of temperature rise as a function of exposure time at a depth of 500μ did not agree particularly well in general with our measured temperature-time profiles even up to the point of shut-off of the heat pulse. One of the reasons for these discrepancies is, undoubtedly, related to the fact that neither the specific heat nor the thermal conductivity of the polymeric fabrics tested is constant with increasing temperature as the theoretical treatment assumes. Additional discrepancies may result from less than perfect contact between the fabric layer and the skin simulant.

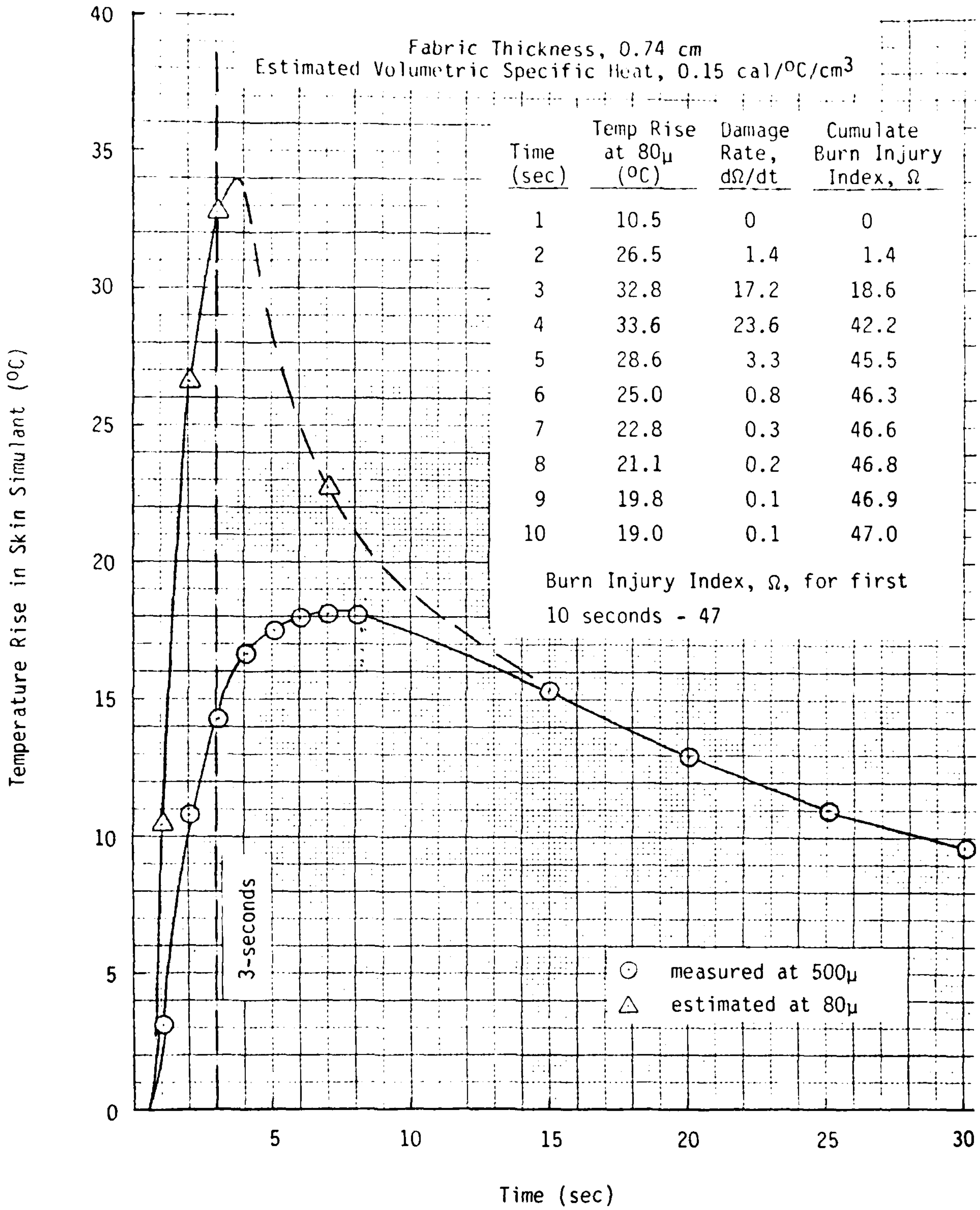
There seems to exist a real need for either: extending and refining the analytical treatment of heat flow through the two-layer system so that the resulting theoretical temperature-time characteristics more closely agree with the actual responses measured during exposure, both during flame-impingment and during the subsequent period following cessation of the flame in which maximum temperature is achieved and cooling begins; or rethinking entirely the use and appropriateness of skin simulant sensors as indicators of the extent of burn injury.

With the foregoing limitations in mind, we nevertheless attempted to extract some estimate of the protective capability of each of the various outerwear fabrics and outerwear/underwear fabric assemblies in terms of burn injury potential as determined by a procedure patterned after Stoll's temporal integral of the burn injury rate vs. time curve. This process involved the following steps, illustrated in Figure 59 and described in more detail below:

1. Conversion of the temperatures measured in the skin simulant at a depth of 500μ to estimated temperatures at 80μ.

2. Determination of burn injury rate as a function of exposure time from the 80μ temperature-time curve and the tissue damage rate data of Stoll[14].

3. Numerical integration of the burn injury rate curve to obtain an estimate of burn injury index.



Time (sec)	Temp Rise at 80μ (°C)	Damage Rate, dΩ/dt	Cumulate Burn Injury Index, Ω
1	10.5	0	0
2	26.5	1.4	1.4
3	32.8	17.2	18.6
4	33.6	23.6	42.2
5	28.6	3.3	45.5
6	25.0	0.8	46.3
7	22.8	0.3	46.6
8	21.1	0.2	46.8
9	19.8	0.1	46.9
10	19.0	0.1	47.0

Figure 59. Typical Example of Temperature Conversion to 80μ Depth and Calculation of Burn Injury Index (single layer fabric 3)

The first step in the temperature conversion process involved replotting the actual time-temperature traces recorded during flame-impingement (Figure 54) in terms of temperature <u>increase</u> from the initial starting temperature. This step is necessary since our starting temperatures varied somewhat while all of Stoll's damage rate data is based on a starting temperature of 32.5°C. Therefore, all temperature measurements were interpreted in terms of temperature rise rather than absolute temperature achieved, in the manner illustrated in Figure 59. Next, conversion graphs such as those given in Figure 60 computed from Stoll's heat flow equation for particular values of volumetric specific heat and an intermediate value of thermal conductivity (1.0×10^{-4} cal/sec/°C/cm) were employed to estimate the temperature rise at 80μ from the actual measured temperature rise at 500μ for the first 3- or 6-seconds of exposure only. Volumetric specific heats of each of the fabrics were estimated from a value of specific heat of 0.32 cal/g/°C and measured fabric densities. Conversion graphs computed for the value of volumetric specific heat closest to the estimated value were then used to obtain temperatures at 80μ. (Individual sets of curves were drawn for fabric thicknesses ranging between 0.01 and 0.16 cm and volumetric specific heats of 0.05, 0.10, 0.15 and 0.20 cal/°C/cm^3 of which the two sets plotted in Figure 60 are representative.) Maximum temperature rise may be assumed to occur at 80μ before it occurs at 500μ; however, since we have no way of estimating the time difference from the heat-flow equation, as discussed previously, we have arbitrarily chosen the fraction of 80/500 of the total time between flame shut-off and the attainment of the maximum at 500μ as the time of maximum temperature rise at 80μ, and we have extended our 80μ curve accordingly to this point, as shown in Figure 59. One additional point is plotted on the temperature curve for the 80μ depth and this was obtained from the computer generated data by taking the ratio of the temperature at 80μ to the temperature at 500μ at the maximum temperature for the 500μ depth. The 80μ curve is extrapolated from this last estimated point to rejoin the actual 500μ response curve at long times.

Burn injury rates were then estimated at one-second intervals from the 80μ temperature rise curve and tissue damage data from Figure 2 of Stoll's paper, Ref. 16. Her damage rate data may be summarized in analytical terms as follows:

damage rate, $d\Omega/dt = be^{cU_2(t)}$

where Ω = burn injury index (arbitrary units)

t = time (sec)

U_2 = temperature rise at the 80μ depth at time t (°C);

and $b = 0$ for $U_2 < 11.5$°C (skin temperature below 44°C),

$b = 4.82 \times 10^{-9}$ and $c = 0.912$ for 11.5°C $\leq U_2 \leq$ 17.5°C (skin temperature between 44°C and 61.5°C),

$b = 4.20 \times 10^{-5}$ and $c = 0.394$ for 17.5°C $\leq U_2 \leq$ 39.5°C (skin temperature between 61.5°C and 72°C).

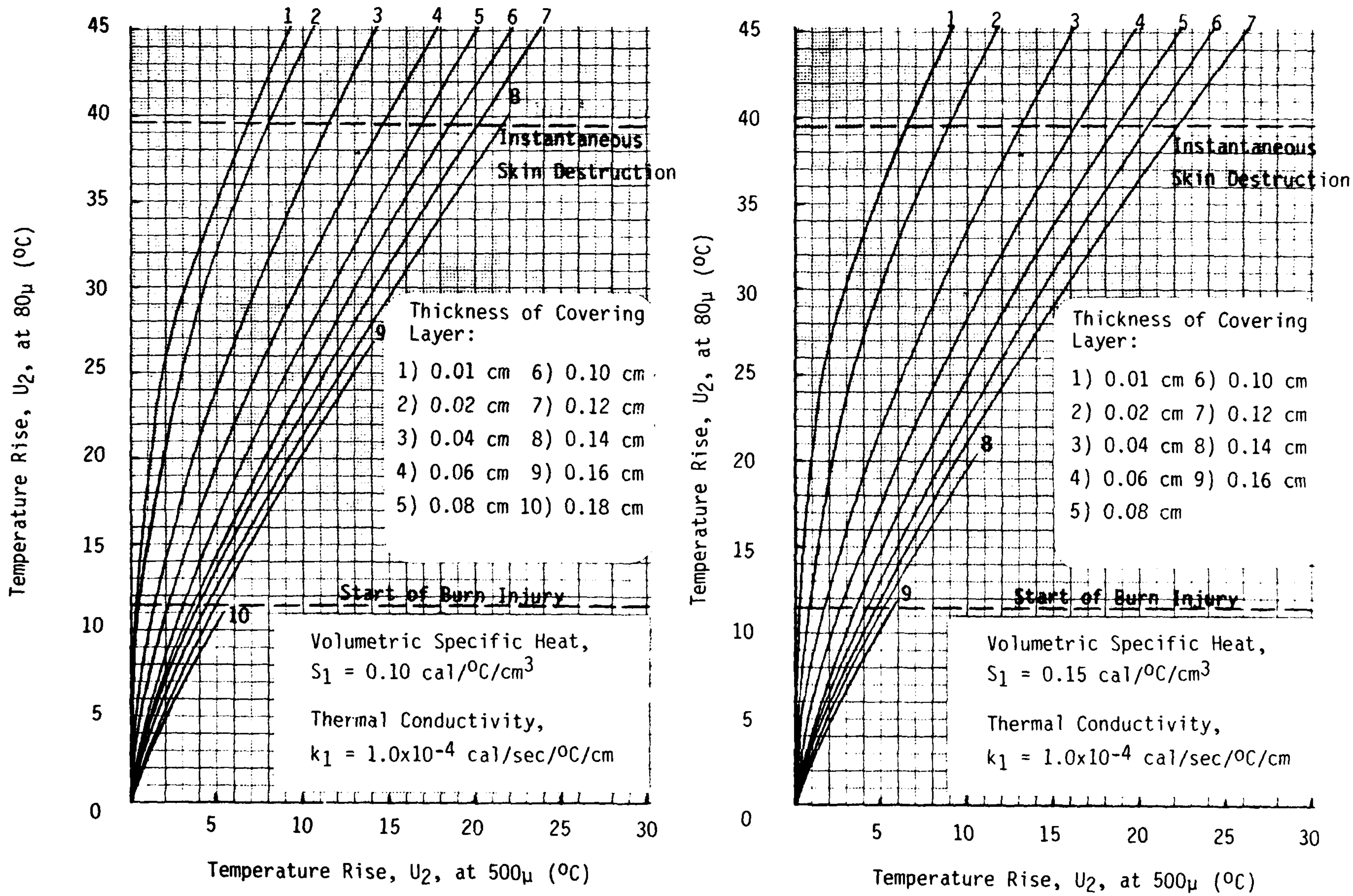


Figure 60. Theoretical Temperature Rise in Skin Simulant During Flame Impingement for Typical Fabric Parameters (2.2 cal/cm^2/sec, 6-second exposure)

For temperature increases greater than 39.5°C at a depth of 80μ in the skin simulant (equivalent to a skin temperature in excess of 72°C), the burn injury index may be taken as infinite. Damage rate calculations based on the above expression specifically for the temperature rise data presented in Figure 59 are summarized in the figure. Numerical integration of the damage rate data was performed by effectively adding the areas under one-second slices of the damage rate vs. time curve for the first 10 seconds of exposure. (The damage rate curve was not actually plotted in each instance; it was plotted, however, for the values in Figure 59 in order to check that this procedure resulted in a reasonably accurate estimate of the area under the curve. Agreement was excellent - 47 from numerical integration and 46 from actual area measurement).

The above procedure was repeated with typical temperature rise-time graphs for each of the fabrics and fabric assemblies tested; the estimates of burn injury index so obtained are listed in Table 5. Because the temperature conversion to an 80μ depth was obtained in a less than rigorous manner, the values of burn injury index given in Table 5 may easily be in error by a factor of two or three. If a temperature rise greater than 39.5°C was estimated at any time during exposure at the 80μ depth, a value of infinity was entered for the burn injury index in the table.

A burn injury index of infinity was calculated for all of the fabrics and assemblies after exposures of 6-seconds duration, with the exception of those fabric assemblies which included the thick 100% wool outerwear fabric 14. Values calculated for the burn injury index for the various outerwear fabrics tested singly after an exposure period of 3 seconds were also generally very high or infinite; only those for three of the thickest fabrics in the series, nos. 1, 3 and 14, were estimated at less than infinite and of these, the low value of 3.8 for the 100% wool fabric 14 is still considerably above the blister end-point level of unity. Among the various outerwear/underwear fabric assemblies, burn injury index values range from a low of 0.1 for certain combinations with the wool fabric 14 to infinity for combinations with some of the lighterweight outerwear fabrics. Only for a few of the fabric assemblies tested are the estimates of burn injury index less than the blister end point of unity; these include each of the four combinations with wool fabric 14 and the combination of 100% polyester doubleknit fabric 9 with the 100% cotton knit underwear fabric 19. Other relatively low values, although above the blister end point, were obtained for outerwear fabric 9 in combination with knit underwear fabric 20 (2.2); 50/50 nylon/cotton outerwear fabric 4 with 100% cotton underwear fabric 21 (3.9); and 35/65 polyester/cotton outerwear fabric 1 with 100% cotton underwear fabric 21 (4.9).

The values of maximum temperature rise at 500μ as measured in the skin simulant during a 3-second exposure and temperature rise at 3 seconds during a 3-second exposure which are given in Table 5 for the various fabrics and assemblies are plotted in Figures 61 and 62 respectively vs. burn injury index. As can be seen from these figures, neither maximum temperature rise at 500μ nor temperature rise at 3 seconds measured at 500μ are good predictors of burn injury index since the range of values of the index for a particular value of temperature rise is wide: for example, for a maximum temperature rise of about 15°C measured in the skin simulant, the burn injury index ranges between 2.2 and 16. The burn injury index is very dependent on the maximum temperature rise at 80μ because the burn injury rate increases rapidly with increasing temperature of the basal layer of the skin; however, the calculated temperature rise at 80μ depends not only on the measured rise at 500μ but also on the thickness and thermal properties of the fabric layer. It would seem that estimates of burn injury based on a single temperature measured in a skin simulant could easily be in error by an order of magnitude.

Those fabric combinations that offer the best protection to burns encountered during direct exposure to short-term, high-intensity flame impingement are, primarily, those which are thicker, and, in addition, either contain a large amount of sorbed water (wool, cotton) or a melting fraction (polyester, nylon) both of which serve to minimize the temperature increase in the skin simulant by momentarily increasing the specific heat capacity of the covering layer.

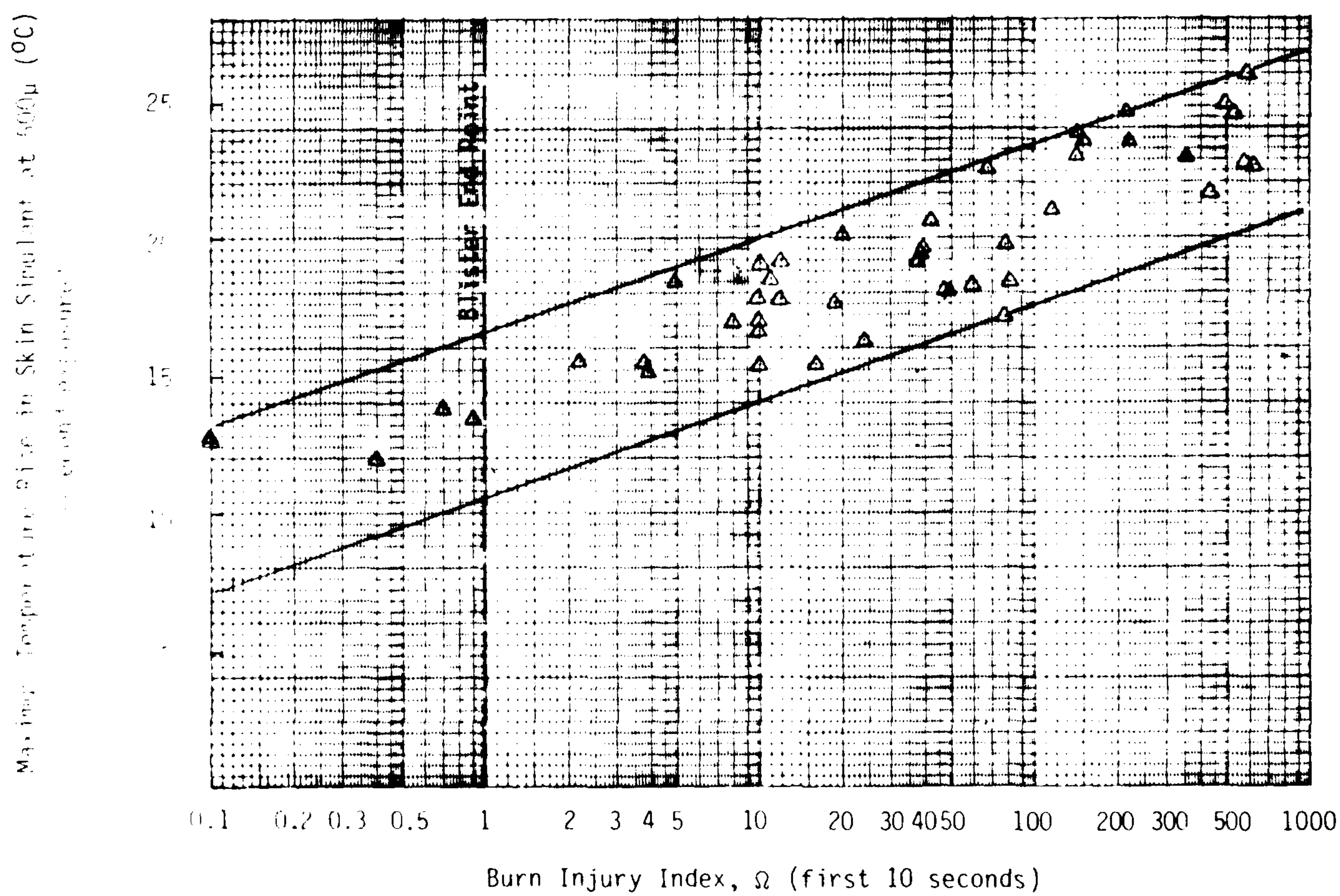


Figure 61. Variation of Burn Injury with Maximum Temperature Rise in Skin Simulant at a Depth of 500μ ($2.2\ cal/cm^2/sec$, 3-second exposure)

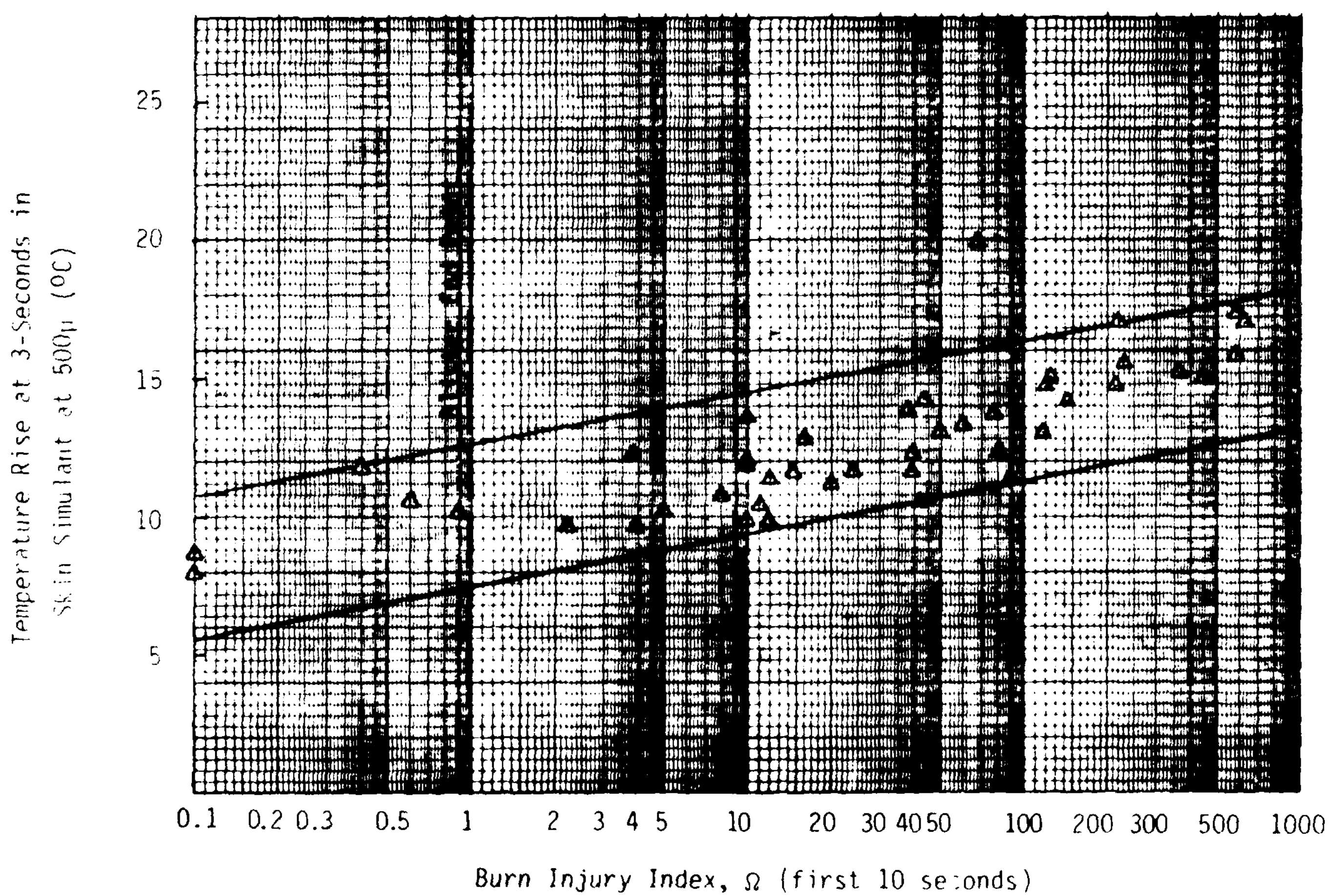


Figure 62. Variation of Burn Injury Index with Temperature at 3-Seconds in Skin Simulant at a Depth of 500μ (2.2 $cal/cm^2/sec$, 3-second exposure)

VI. SUMMARY AND CONCLUSIONS

The characteristics of clothing materials that are important for short-term protection from intense heat are: the ability to retard both radiative and conductive heat transfer; the ability to resist ignition; and the ability to retain mechanical strength so that fabric integrity and, hence, protective cover is maintained for an active wearer. All of these factors are ultimately determined by the temperature achieved in the material during exposure and the properties of the material at that temperature. The most that can be expected of ordinary Navy shipboard work clothing is that it offer sufficient protection that rapid escape from the vicinity of a fire hazard is possible. To this end, any quality of the fabric of such clothing that slows the rate of temperature increase within the material or causes the temperature achieved to have less disastrous effects on the material properties will be an advantage. It is the transient thermal properties that are of most interest in defining the protective capacity of a fabric, properties measured at short times during exposure to intense heat.

As the result of the work on a wide range of materials reported herein, it is possible to distinguish those fabric characteristics which most affect the rate of temperature rise in a radiative environment and during direct exposure to a flame. We have assessed the effects of rapid temperature increase on residual fabric strength, likelihood of ignition, heat transfer to underlying surfaces and, in a limited way, the extent of burn injury that may be expected to occur.

We have found that those fabric characteristics which most effect the rate of temperature rise in the material during exposure to intense radiant heat are fabric weight and polymer composition. Difference between fabric surface optical properties (absorptance, emittance) are minor within the series of fabrics tested since none were highly reflective, nor highly napped; color, at the dominant wavelengths in a large fire has little effect on fabric absorptive capacity. Consequently, differences in the rate at which radiant heat is absorbed during exposure are small, and the rate at which comparative increases in temperature occur is then largely dependent on fabric weight (mass) and material specific heat.

Fabrics in the weight range studied which contain large amounts of sorbed water, such as those high in cotton or wool content, may provide a delay of 1 or 2 seconds in temperature increase above the 100°C level because of the high heat of vaporization of water. Similarly, for those fabrics which consist of a large thermoplastic fraction, polyester or nylon, the high heats of fusion can result in a delay of about 2- to 4-seconds in temperature increase past the melting temperature of the polymer. However, such materials are not necessarily superior in performance to others in which the temperature increase proceeds more smoothly but the rate of degradation of mechanical properties is less rapid. Thermoplastic materials may delay the rate of temperature increase past a certain level but their mechanical properties deteriorate completely at temperatures close to melting; unless they are used in combination with a polymer which retains strength at these temperatures and above, their advantage is lost. When the results of our testing are normalized for fabric weight, the Nomex/Kevlar material is shown able to maintain some strength for longer periods of time than the other materials tested at the lower exposure intensities (500°C, 0.4 cal/cm^2/sec and below) (see Figures 40 and 41). However, at the highest level used in the investigation of mechanical properties (560°C, 0.5 cal/cm^2/sec) the Nomex/Kevlar is no better as a material than 100% cotton, 100% wool, or 50/50 nylon/cotton: all lose 90% of their original strength within 4- to 5-seconds of the start of exposure at this more intense condition (see Figure 42). Comparative data for PBI fabric (polybenzimidazole) available from other work[1,9] shows this polymer to retain strength longer than the materials in this test series at the 560°C, 0.5 cal/cm^2/sec exposure level but under more intense conditions, this material also loses all strength rapidly.

Ignition generally occurs only a short time after the fabrics have lost all mechanical strength. The occurrence of ignition depends on the temperature achieved during exposure, the rate of temperature increase[1], and the rate at which polymer decomposition proceeds. When comparisons are made between the fabrics on an equal weight basis, the Nomex/Kevlar, the 100% wool material, and some of the wool blends resisted ignition for longer periods of time than the other materials in the series at exposure conditions to 650°C, 0.7 cal/cm^2/sec (see Figures 43 to 45).

The transfer of heat to an underlying surface from a fabric or fabric assembly exposed to intense radiant heat has been shown by calorimeter measurements to be largely independent of fabric openness or transmissibility since the sum of transmitted, reradiated and conducted energy received by the inner surface does not vary much with fabric type and construction under the same exposure conditions. Exothermic reactions within the fabric, including ignition, can supply more heat to the interior than is incident on the exterior. Additional layers in the form of underwear fabric tend to diminish the amount of heat transferred.

Measurements of temperature rise in a skin simulant material during short, timed exposures of fabrics and fabric assemblies to a gas flame at 2.2 cal/cm^2/sec are more sensitive indicators of the effect of fabric structure and composition on rate of heat transfer. The maximum temperature achieved in the simulated skin under these conditions has been shown to be minimized by fabric assemblies which are slow to heat their inner surface. Greater assembly thickness is the most important factor in diminishing the rate of heat flow to the interface between fabric and skin. Fabric weight and polymer specific heat are also important since fabrics of greater weight and higher specific heat are slower to increase in temperature. The extent of burn injury from heat transfer through a covering layer of fabric is estimated to be least for those fabrics which are thickest and for which the specific heat is boosted by the presence of sorbed water or a thermoplastic fraction.

In order to assess the total protective capacity of a fabric or fabric assembly, each aspect of its behavior during exposure to the intense heat of a fire must be taken into account. It is clear from the investigation summarized herein that fabric weight and thickness are of principal importance in determining the amount of protection offered. A heavy fabric is slow to heat and, therefore, slower to lose strength and ignite; a thick fabric is, in addition, slow to transfer heat to an inner surface. The ideal fabric for a protective garment would be heavy, thick, and composed of a high-temperature material such as Nomex/Kevlar or PBI, each of which decompose relatively slowly at moderately high temperatures. Unfortunately, heavy, thick clothing is generally uncomfortable to wear. Therefore, the degree of protection offered must be balanced with the comfort needs of the wearer in terms of the degree of risk of exposure in determining the ideal fabric structure for Navy shipboard work clothing.

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Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure to Various Bilateral Radiant Heat Flux Levels

Fabric Description	Radiant Heat Flux (cal/cm²/sec)	Heater Temp (°C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture		Modulus (lb/inch width/ unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #1	--	20	--	--	Avg	1400	181	100
35/65 polyester/cotton								
10.3 oz/sq yd	0.1	270	0	12		1140	127	
70 x 44						1320	135	
						1410	130	
					Avg	1290	131	72
			5	17		1290	120	
						1200	114	
						1010	108	
					Avg	1200	114	63
			10	21		1140	106	
						1140	112	
						1140	104	
					Avg	1140	107	59
			20	30		1300	95	
						1120	96	
						1180	102	
					Avg	1200	98	54
			60	70		1150	96	
						--	93	
						950	96	
						940	88	
						830	83	
					Avg	1050	91	50
	0.2	350	0	11		1020	93	
						1130	99	
						730	92	
					Avg	960	95	52
			5	16		920	86	
						850	90	
						750	83	
					Avg	840	86	48
			10	21		960	77	
						1010	84	
						820	81	
					Avg	930	81	45
			20	32		650	70	
						620	73	
						630	75	
					Avg	630	73	40
			60	69		590	49	
						620	75	
						870	48	
						660	39	
						960	44	
					Avg	740	51	28

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure to Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux ($cal/cm^2/sec$)	Heater Temp (^oC)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture		Modulus (lb/inch width/unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #1 (cont)	0.25	400	0	12		790	75	
35/65 polyester/cotton						940	69	
10.3 oz/sq yd						710	69	
70 x 44						850	71	
						860	71	
					Avg	830	71	39
			5	16		675	46	
						--	53	
						510	38	
						380	39	
					Avg	522	44	24
			10	20		430	28	
						530	31	
						530	35	
					Avg	500	31	17
			20	32		500	23	
						280	21	
						510	32	
						420	29	
						230	19	
						340	22	
						---	30	
						360	13	
					Avg	380	27	15
			30	38		25	2	
						130	7	
						392	18	
						180	9	
						170	8	
					Avg	180	9	5
			40	46		35	2	
						200	10	
						--	3	
						57	3	
						24	1	
					Avg	99	4	2
	0.4	500	0	11		270	18	
						260	19	
						300	21	
					Avg	290	19	10
			5	13		--	5	
						69	4	
						58	3	
					Avg	64	4	2
			10	15		--	0.5	
						--	0.2	
					Avg		0.4	<1
	0.5	560	0	8		56	3	
						38	2	
						33	2	
					Avg	42	2	1
			5	10		--	0.4	
						--	0.6	
						--	0.2	
					Avg		0.4	<1

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux (cal/cm²/sec)	Heater Temp (°C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture		Modulus (lb/inch width/unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #2, 55/45	--	20	--	--	Avg	520	85	100
polyester/wool,								
6.4 oz/sq yd	0.1	270	0	12		400	64	
62 x 52						390	62	
						400	67	
					Avg	400	64	75
			5	17		360	63	
						350	58	
						350	60	
					Avg	350	60	71
			10	21		310	57	
						350	59	
						310	54	
					Avg	330	57	67
			20	31		290	56	
						300	54	
						310	55	
					Avg	300	55	65
			60	70		320	52	
						310	51	
						330	54	
					Avg	320	52	61
	0.2	350	0	10		280	38	
						290	41	
						310	41	
					Avg	290	40	47
			5	13		200	21	
						230	33	
						190	20	
						270	25	
						190	23	
					Avg	210	24	28
			10	15		180	15	
						140	11	
						150	11	
					Avg	160	12	14
			15	20		20	1	
						40	3	
						10	1	
						10	<1	
						40	3	
						60	6	
						20	1	
					Avg	30	2	2
	0.25	400	0	7		180	21	
						190	21	
						190	21	
					Avg	190	21	25
			5	10		100	6	
						100	6	
						90	5	
					Avg	100	6	7
	0.4	500	0	4		30	2	
						40	2	
						40	2	
						30	2	
						30	2	
					Avg	30	2	2
	0.5	560	0	3		40	2	
						20	1	
						20	1	
					Avg	30	1	2

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux (cal/cm²/sec)	Heater Temp (°C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture	Modulus (lb/inch width/unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #3	--	20	--	--	Avg 1340	138	100
100% cotton							
10.3 oz/sq yd	0.1	270	0	11	1320	110	
68 x 42					1420	118	
					1440	117	
					Avg 1390	115	83
			5	16	982	94	
					1310	96	
					1300	90	
					Avg 1200	93	67
			10	21	1010	94	
					1000	94	
					720	82	
					Avg 910	90	65
			20	31	820	83	
					960	86	
					890	83	
					Avg 890	84	61
			60	70	800	76	
					1010	75	
					1010	77	
					Avg 940	76	55
	0.2	350	0	10	1150	88	
					1120	88	
					1190	85	
					1150	87	63
			5	15	839	73	
					1070	76	
					1090	79	
					Avg 1030	76	55
			10	20	950	65	
					920	66	
					870	66	
					910	66	48
			20	29	830	58	
					800	58	
					930	62	
					Avg 850	59	43
			60	69	800	46	
					660	42	
					682	49	
					Avg 710	46	33
	0.25	400	0	10	930	71	
					920	72	
					670	74	
					900	72	52
			5	15	760	58	
					740	60	
					780	57	
					Avg 760	58	42
			10	19	630	43	
					630	48	
					700	42	
					Avg 650	44	32
			20	27	210	11	
					260	15	
					90	6	
					110	7	
					400	22	
					530	26	
					560	30	
					310	17	10
			25	30	130	10	
					52	4	
					90	4	
					130	7	
					240	11	
					Avg 130	7	5

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux (cal/cm²/sec)	Heater Temp (°C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture		Modulus (lb/inch width/unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #3 (cont)	0.4	500	0	9		310	24	
100% cotton						430	23	
10.3 oz/sq yd						550	24	
68 x 42						292	22	
						440	23	
					Avg	400	23	25
			5	12		97	16	
						190	19	
						140	17	
						100	16	
						60	15	
					Avg	120	17	5
	0.5	560	0	6		140	11	
						140	9	
						140	9	
						60	5	
						60	6	
					Avg	110	8	6
Fabric # 4	--	20	--	--		980	155	100
50/50 nylon/cotton								
9.3 oz/sq yd	0.1	270	0	10		930	126	
112 x 76						970	128	
						950	128	
					Avg	950	127	82
			5	15		930	114	
						920	118	
						920	119	
					Avg	920	117	76
			10	20		860	106	
						920	106	
						890	108	
					Avg	890	107	69
			20	30		800	96	
						820	103	
						800	96	
					Avg	810	98	63
			60	71		710	92	
						700	95	
						700	93	
					Avg	700	93	60
	0.2	350	0	9		950	100	
						930	103	
						960	103	
					Avg	950	102	66
			5	16		760	80	
						810	83	
						820	81	
					Avg	800	81	52
			10	22		640	68	
						700	72	
						710	76	
					Avg	680	72	47
			20	27		520	42	
						570	58	
						610	75	
						500	44	
						530	41	
					Avg	550	52	34
			60	63		220	11	
						300	9	
						460	11	
					Avg	330	10	7

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux (cal/cm^2/sec)	Heater Temp (^oC)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture		Modulus (lb/inch width/ unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #4 (cont)	0.25	400	0	8		840	81	
50/50 nylon/cotton						910	85	
9.3 oz/sq yd						880	80	
112 x 76						910	80	
					Avg	880	82	53
			5	15		690	69	
						680	71	
						550	57	
						600	57	
						630	57	
					Avg	630	62	40
			10	15		450	41	
						450	39	
						490	45	
					Avg	460	42	27
			20	23		190	10	
						190	10	
						170	7	
					Avg	180	9	6
			40	42		30	1	
						30	1	
						30	1	
					Avg	30	1	1
	0.4	500	0	6		570	50	
						580	52	
						600	50	
					Avg	580	51	33
						150	10	
						170	13	
						140	9	
						140	10	
						140	8	
					Avg	150	10	7
	0.5	560	0	5		510	37	
						500	35	
						480	35	
					Avg	500	36	23
			5	8		50	3	
						20	1	
						30	2	
					Avg	30	2	1

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux ($cal/cm^2/sec$)	Heater Temp (^{o}C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture	Modulus (lb/inch width/ unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #6	---	20	--	--	1870	134	100
65/35 polyester/cotton							
7.0 oz/sq yd	0.1	270	0	8	1650	96	
84 x 56					1540	97	
					1540	101	
					1550	102	
					Avg 1570	99	74
			5	13	1230	91	
					1150	89	
					1210	87	
					Avg 1200	89	66
			10	18	1160	88	
					1170	82	
					1240	89	
					Avg 1190	86	64
			20	28	1020	78	
					1080	85	
					1150	85	
					Avg 1090	83	62
			60	68	1140	92	
					1050	83	
					940	78	
					1030	79	
					1240	84	
					Avg 1080	83	62
	0.2	350	0	7	1400	79	
					1480	83	
					1470	83	
					Avg 1450	82	61
			5	13	990	68	
					990	57	
					1040	73	
					1080	74	
					1011	61	
					Avg 1023	67	50
			10	14	840	32	
					790	30	
					830	45	
					800	38	
					730	20	
					660	16	
					Avg 680	30	22
			20	21	---	<1	<1
	0.25	400	0	8	1330	70	
					1320	67	
					1190	61	
					1210	62	
					1450	73	
					Avg 1300	67	50
			5	8	750	17	
					800	21	
					790	20	
					920	32	
					960	35	
					810	19	
					940	41	
					Avg 850	26	19
			10	11	1	124	
					1	72	
					2	95	
					Avg 1	97	1

Appendix Table 1. **Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)**

Fabric Description	Radiant Heat Flux (cal/cm²/sec)	Heater Temp (°C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture		Modulus (lb/inch width/unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #6 (cont)	0.4	500	0	2		890	35	
65/35 polyester/cotton						920	35	
7.4 oz/sq yd						830	31	
84 x 56					Avg	880	33	25
			5	1		---	<1	<1
	0.5	560	0	2		750	24	
						790	26	
						790	27	
					Avg	780	26	19
			5	--		0	0	0
Fabric #7	--	20	--	--	Avg	1420	146	100
50/50 polyester/cotton								
6.9 oz/sq yd	0.1	270	0	5		1200	112	
108 x 56						1230	112	
						1210	112	
					Avg	1210	112	77
			5	11		1080	89	
						1080	87	
						1080	93	
					Avg	1080	90	62
			10	16		1050	82	
						1020	82	
						1020	82	
					Avg	1030	82	56
			20	26		1010	78	
						1000	76	
						1010	77	
					Avg	1010	77	53
			60	67		1120	77	
						1040	73	
						1020	74	
					Avg	1060	75	51
	0.2	350	0	5		960	86	
						990	87	
						1050	88	
					Avg	1000	87	60
			5	11		960	68	
						960	67	
						880	69	
					Avg	940	68	47
			10	13		870	42	
						871	37	
						760	34	
					Avg	830	38	26
			20	22		490	12	
						470	11	
						540	12	
					Avg	500	12	8
			60	62		210	5	
						307	7	
						370	8	
						290	8	
						280	10	
					Avg	290	8	5

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux (cal/cm²/sec)	Heater Temp (°C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture		Modulus (lb/inch width/unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #7 (cont)	0.25	400	0	4		910	71	
50/50 polyester/cotton						870	72	
6.9 oz/sq yd						910	75	
108 x 56					Avg	900	73	50
			5	8		800	38	
						840	40	
						930	37	
					Avg	860	38	26
			10	12		410	10	
						371	9	
						430	11	
					Avg	400	10	7
			20	22		200	4	
						230	4	
						240	5	
					Avg	220	4	3
						70	1	
						80	2	
						50	1	
					Avg	70	1	1
	0.4	500	0	3		640	9	
						680	8	
						650	8	
					Avg	660	8	32
			5	7		200	6	
						190	5	
						200	5	
					Avg	210	6	3
	0.5	560	0	3		500	27	
						430	28	
						500	31	
					Avg	490	29	20
Fabric #8	--	20	--	--		520	60	100
75/25 polyester/wool								
6.4 oz/sq yd	0.1	270	0	7		380	40	
52 x 44						370	40	
						380	42	
					Avg	370	41	68
			5	12		320	41	
						310	38	
						290	42	
					Avg	300	40	67
			10	17		270	38	
						260	36	
						280	35	
					Avg	270	36	60
			20	27		270	35	
						290	36	
						280	32	
					Avg	280	34	57
			60	67		290	33	
						310	33	
						320	35	
					Avg	310	34	57

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux ($cal/cm^2/sec$)	Heater Temp (^{o}C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture		Modulus (lb/inch width/ unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #8 (cont)	0.2	350	0	8		190	30	
75/25 polyester/wool						220	33	
[illegible].4 oz/sq yd						220	29	
52 x 44					Avg	210	31	52
			5	11		160	18	
						200	20	
						170	16	
					Avg	170	18	30
			10	13		90	5	
						80	4	
						70	3	
					Avg	80	4	7
			15	16		--	<1	<1
	0.25	400	0	7		130	15	
						150	20	
						160	20	
						170	19	
						150	18	
					Avg	150	19	32
			5	8		20	1	
						30	2	
						10	1	
					Avg	20	1	2
	0.4	500	0	3		80	6	
						50	3	
						50	3	
						30	1	
						30	1	
					Avg	50	3	5
	0.5	560	0	2		20	1	
						20	1	
						20	1	
						20	1	
					Avg	20	1	1
Fabric #9	--	20	--	--		90	54	100
100% polyester								
6.0 oz/sq yd	0.2	350	0	12		--	12	
36 x 24						--	7	
						--	12	
						--	7	
						--	10	
					Avg	--	9	17
			5	13		--	2	
						--	2	
						--	1	
						--	1	
						--	1	
					Avg	--	1	3
			10	15			<1	
							<1	
							1	
							<1	1
	0.25	400	0	8		--	1	
						--	<1	
						--	1	
						--	<1	
						--	<1	
					Avg	--	<1	
	0.4	500				melted		
	0.5	560				melted		

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux (cal/cm^2/sec)	Heater Temp (°C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture		Modulus (lb/in width/ unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #10, 65/35 polyester/rayon	--	20	--	--		610	93	100
5.9 oz/sq yd 56 x 48	0.1	270	0	8		490	70	
						520	67	
						500	67	
					Avg	500	68	73
			5	14		460	59	
						440	61	
						450	66	
					Avg	450	62	67
			10	19		500	64	
						460	63	
						470	59	
					Avg	480	62	67
			20	28		470	59	
						450	58	
						480	58	
						---	62	
					Avg	470	59	63
			60	69		520	59	
						500	61	
						510	61	
					Avg	510	60	65
	0.2	350	0	9		410	55	
						390	56	
						410	55	
					Avg	400	55	59
			5	13		380	41	
						360	49	
						360	45	
					Avg	370	45	48
			10	15		310	24	
						320	19	
						300	17	
						320	20	
						350	37	
						304	17	
					Avg	320	22	24
			15	17		150	4	
						100	3	
						110	4	
						150	7	
						120	4	
					Avg	130	4	4
	0.25	400	0	8		330	38	
						340	42	
						330	38	
					Avg	330	39	42
			5	8		270	13	
						250	11	
						300	16	
						260	11	
						340	21	
					Avg	280	14	15
			10	11		50	1	
						80	1	
						60	1	
					Avg	60	1	2

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux ($cal/cm^2/sec$)	Heater Temp (°C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture		Modulus (lb/in width/ unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #10 (cont)	0.4	500	0	4		200	14	
65/35 polyester/rayon						230	16	
5.9 oz/sq yd						230	15	
56 x 48					Avg	220	15	16
			5	--		0	0	0
	0.5	560	0	3		160	9	
						190	12	
						200	11	
						140	7	
						120	6	
					Avg	160	7	8
			5	--		0	0	0

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux (cal/cm^2/sec)	Heater Temp (^{o}C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture		Modulus (lb/inch width/unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #11	--	20	--	--		1370	59	100
50/50 polyester/cotton								
[illegible] oz/sq yd	0.1	270	0	2		1210	43	
[illegible] x 46						1110	45	
						1150	47	
					Avg	1160	45	76
			5	8		1050	38	
						990	37	
						950	37	
					Avg	1000	37	63
			10	14		940	37	
						860	36	
						890	37	
					Avg	900	37	63
			20	24		830	34	
						840	37	
						920	36	
					Avg	860	36	61
			60	64		940	38	
						960	38	
						840	37	
					Avg	910	38	64
	0.2	35	0	3		970	34	
						1020	34	
						990	34	
					Avg	990	34	58
			5	6		630	14	
						640	17	
						580	14	
						600	16	
						600	12	
					Avg	610	15	25
			10	11		130	1	
						140	1	
						190	1	
					Avg	150	1	2
	0.25	400	0	2		930	29	
						810	29	
						940	31	
					Avg	890	30	51
			5	5		100	1	
						140	1	
						130	1	
					Avg	120	1	2
	0.4	500	0	1		640	17	
						710	17	
						700	19	
					Avg	690	18	31
			5	--		0	0	0
	0.5	560	0	1		520	9	
						540	10	
						610	12	
						430	9	
						530	10	
					Avg	530	10	17
			5	--		0	0	0

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux (cal/cm^2/sec)	Heater Temp (°C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture	Modulus (lb/inch width/ unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #12	--	20	--	--	1570	90	100
65/35 polyester/cotton							
4.8 oz/sq yd	0.1	270	0	7	1260	54	
92 x 72					1290	56	
					1170	51	
					Avg 1240	54	60
			5	12	900	46	
					930	48	
					950	48	
					Avg 930	47	52
			10	17	940	48	
					970	50	
					850	48	
					Avg 920	49	54
			20	27	930	49	
					760	48	
					880	48	
					Avg [illegible]60	48	53
			60	68	810	47	
					870	49	
					940	50	
					Avg 870	49	54
	0.2	350	0	7	920	44	
					950	44	
					950	43	
					Avg 940	44	49
			5	10	730	30	
					780	33	
					710	20	
					680	21	
					810	36	
					Avg 740	28	31
			10	12	520	10	
					460	7	
					630	14	
					510	10	
					520	12	
					Avg 520	10	12
			20	22	90	2	
					130	2	
					130	2	
					Avg 120	2	2
			60	61	110	2	
					90	1	
					140	2	
					Avg 110	2	2
	0.25	400	0	5	850	26	
					840	29	
					770	25	
					780	25	
					830	27	
					Avg 810	26	29
			5	6	280	6	
					340	8	
					270	7	
					Avg 290	7	7
			10	12	80	1	
					100	2	
					70	1	
					Avg 80	1	2
			20	21	30	<1	
					40	<1	
					30	<1	<1

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux (cal/cm²/sec)	Heater Temp (°C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture		Modulus (lb/inch width/ unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #12 (cont)	0.4	500	0	2		640	16	
65/35 polyester/cotton						680	17	
4.8 oz/sq yd						670	17	
92 x 72					Avg	660	17	18
			5	6		---	<1	<1
	0.5	560	0	2		560	11	
						490	11	
						490	10	
					Avg	520	11	12
			5	--		0	0	0

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux (cal/cm^2/sec)	Heater Temp (^{o}C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture	Modulus (lb/inch width/ unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #13 100% polyester	--	20	--	--	Avg 620	164	
6.0 oz/sq yd 69x 60	0.1	270	0	14	490	101	
					420	101	
					490	95	
					Avg 470	99	60
			5	20	470	98	
					530	99	
					510	102	
					Avg 500	100	51
			10	24	490	92	
					480	94	
					490	100	
					Avg 490	95	58
			20	34	490	98	
					500	95	
					510	92	
					Avg 500	95	53
			60	74	460	96	
					500	98	
					520	102	
					Avg 490	99	60
	0.2	350	0	13	370	64	
					410	62	
					390	63	
					Avg 390	63	38
			5	17	410	37	
					380	59	
					370	58	
					390	59	
					390	54	
					Avg 390	53	32
			10	20	390	38	
					350	45	
					360	28	
					420	46	
					410	58	
					Avg 390	43	26
			15	22	90	9	
					100	10	
					40	5	
					180	13	
					110	8	
					Avg 100	9	6
			20	27	340	39	
					150	10	
					40	3	
					50	3	
					70	5	
					210	46	
					70	5	
					230	16	
					130	9	
					Avg 140	15	9
			25	31		2	
						1	
						1	
						<1	
						1	
						1	0.5
	0.25	400	0	9	180	14	
					200	13	
					260	22	
					200	14	
					310	32	
					Avg 230	19	12
	0.4	500			melts immediately		
	0.5	560			melts immediately		

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux ($cal/cm^2/sec$)	Heater Temp (^{o}C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture		Modulus (lb/in width/ unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #14	--	20	--	--		310	33	100
100% wool	0.1	270	0	9		240	28	
8.4 oz/sq yd						240	28	
56 x 50						240	29	
					Avg	240	28	85
			20	27		230	24	
						240	26	
						250	26	
					Avg	240	25	76
			60	67		200	19	
						230	21	
						220	21	
					Avg	220	20	61
	0.2	350	0	8		230	27	
						250	28	
						240	27	82
					Avg	240	27	
			10	17		200	16	
						220	20	
						210	18	
					Avg	210	18	55
			20	27		70	4	
						100	7	
						90	6	
						120	8	
						50	3	
					Avg	90	5	16
			30	36		--	<1	
						--	<1	
						--	<1	
					Avg	--	<1	1
			0	8		220	24	
						210	24	
						220	24	
					Avg	220	24	73
			5	12		170	21	
						230	21	
						220	19	
					Avg	210	20	61
			10	15		70	4	
						80	5	
						70	4	
					Avg	70	4	13
			15	17		--	<1	
						--	<1	
						--	<1	
						--	<1	
	0.4	500	0	5		60	5	
						90	6	
						70	7	
					Avg	70	6	19
	0.5	560	0	5		90	7	
						80	5	
						80	5	
					Avg	80	5	16
			5	8		--	<1	1

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux (cal/cm^2/sec)	Heater Temp (^oC)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture		Modulus (lb/inch width/ unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #1[illegible]	--	20	--	--		1220	104	100
65/35 polyester/cotton								
4.4 oz/sq yd	0.1	270	0	9		930	70	
106 x [illegible]						930	74	
						920	77	
					Avg	930	74	71
			5	14		880	67	
						810	66	
						840	67	
					Avg	840	67	64
			10	19		790	68	
						770	69	
						770	65	
					Avg	760	67	64
			20	30		750	65	
						690	64	
						820	68	
					Avg	750	66	64
			60	69		730	65	
						770	63	
						860	68	
					Avg	790	65	63
	0.2	350	0	7		770	39	
						750	43	
						800	47	
						770	47	
						790	47	
					Avg	780	45	43
			5	8		600	19	
						500	18	
						610	22	
					Avg	570	20	19
			10	12		190	5	
						200	5	
						210	5	
					Avg	200	5	5
			20	22		80	2	
						70	2	
						80	2	
						80	2	2
			60	62		57	1	
						63	2	
						34	1	
					Avg	54	1	1
	0.25	400	0	3		700	25	
						670	25	
						720	25	
					Avg	700	25	24
			5	7		110	2	
						90	2	
						80	2	
					Avg	90	2	2
			10	12		40	1	
						40	1	
						50	1	
					Avg	40	1	1

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux (cal/cm² sec)	Heater Temp (°C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture		Modulus (lb/inch width/unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #15 (cont)	0.4	500	0	2		260	7	
65/35 polyester/cotton						380	11	
4.4 oz/sq yd						310	7	
108 x 52						430	12	
						260	6	
						320	9	
						290	9	
					Avg	320	9	8
			5	--		0	0	0
	0.5		0	1		130	2	
						110	2	
						160	3	
					Avg	130	2	2
			5	--		0	0	0

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux (cal/cm²/sec)	Heater Temp (°C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture	Modulus (lb/inch width/unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #16	--	20	--	--	Avg 1380	127	100
65/35 polyester/cotton							
5.8 oz/sq yd	0.1	270	0	8	1080	95	
125 x 54					1020	95	
					1120	95	
					Avg 1070	95	75
			5	14	1050	90	
					980	89	
					1000	91	
					Avg 1010	90	71
			10	19	960	84	
					990	94	
					1020	92	
					Avg 990	90	71
			20	29	950	87	
					950	89	
					1020	90	
					Avg 970	89	71
			60	69	950	88	
					1100	93	
					1020	93	
					Avg 1020	91	72
	0.2	350	0	8	860	79	
					880	81	
					870	72	
					Avg 870	77	61
			5	13	820	58	
					840	66	
					960	75	
					840	68	
					830	74	
					Avg 840	68	54
			10	15	780	62	
					710	40	
					710	28	
					690	46	
					650	26	
					Avg 710	40	32
			20	23	460	11	
					700	27	
					610	16	
					480	18	
					450	10	
					Avg 540	16	13
			6.	62	240	4	
					280	6	
					310	7	
					Avg 280	6	5
	0.25	400	0	6	900	47	
					850	51	
					830	56	
					Avg 860	51	40
			5	7	450	17	
					350	14	
					570	18	
					Avg 460	16	13
			10	12	250	6	
					220	5	
					260	6	
					Avg 240	6	5
	0.4	[illegible]	0	3	520	23	
					550	21	
					640	25	
					Avg 570	23	18
	0.5	560	0	2	320	7	
					390	11	
					350	10	
					360	10	
					240	6	
					Avg 300	9	7

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux ($cal/cm^2/sec$)	Heater Temp (°C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture		Modulus (lb/inch width/ unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #17 95/5 Nomex/Kevlar 4.6 oz/sq yd 72 x 48	--	20	--	--	Avg	900	115	100
	0.1	270	0	9		780	87	
						790	89	
						820	90	
					Avg	800	90	77
			5	13		810	84	
						790	86	
						790	86	
					Avg	800	85	74
			10	18		740	79	
						710	79	
						730	82	
					Avg	730	80	70
			20	28		740	81	
						710	82	
						720	82	
					Avg	720	82	71
			60	68		760	81	
						730	85	
						690	76	
					Avg	730	81	70
	0.2	350	0	8		690	68	
						740	73	
						670	69	
					Avg	700	70	61
			5	12		560	56	
						520	56	
						580	57	
					Avg	550	56	49
			10	17		470	51	
						490	55	
						400	50	
					Avg	450	52	45
			20	27		430	52	
						400	52	
						520	59	
						450	54	
						500	57	
					Avg	460	55	48
			60	67		530	60	
						510	56	
						570	66	
						540	63	
						580	67	
					Avg	550	62	54
	0.25	400	0	7		650	62	
						650	56	
						640	55	
						600	53	
						620	56	
					Avg	630	56	49
			5	12		350	38	
						310	39	
						340	40	
					Avg	340	39	34

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux ($cal/cm^2/sec$)	Heater Temp (°C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture	Modulus (lb/inch width/ unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #17 (cont)	0.25	400	10	17	310	40	
95/5 Nomex/Kevlar					360	42	
4.6 oz/sq yd					370	41	
72 x 48					Avg 340	41	36
			20	26	300	37	
					310	38	
					340	39	
					Avg 320	38	33
			60	66	380	42	
					330	40	
					330	38	
					Avg 350	40	35
	0.4	500	0	6	380	24	
					350	23	
					380	25	
					Avg 370	24	21
			5	8	180	8	
					180	9	
					150	7	
					170	8	7
			10	11	20	1	
					30	1	
					30	1	
					Avg 30	<1	
	0.5	560	0	4	270	14	
					240	11	
					250	12	
					Avg 250	12	8
			5	7	--	<1	<1

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux ($cal/cm^2/sec$)	Heater Temp (^{o}C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture		Modulus (lb/inch width/ unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #18	--	20	--	--		1890	103	100
100% cotton FR								
6.9 oz/sq yd	0.1	270	0	4		2130	86	
124 x 56						2000	94	
						1940	82	
						2030	88	
						2050	91	
					Avg	2030	88	
			5	9		2210	76	
						2270	86	
						2080	79	
						2210	75	
						2210	80	
					Avg	2200	79	77
			10	14		2290	76	
						2030	62	
						2210	72	
						2160	71	
						2060	68	
					Avg	2150	70	68
			20	24		1950	56	
						2060	63	
						2170	58	
					Avg	2060	59	57
			60	64		1970	59	
						2020	55	
						2030	59	
					Avg	2010	58	56
	0.2	350	0	4		2020	84	
						1990	79	
						1710	83	
					Avg	1900	82	80
			5	9		1610	60	
						1820	61	
						1970	64	
					Avg	1800	62	60
			10	13		1810	48	
						1890	49	
						1540	49	
					Avg	1750	49	48
			20	23		1450	40	
						940	27	
						1500	34	
						1310	31	
						1210	36	
					Avg	1370	34	33
			60	61		70	1	
						90	2	
						40	<1	
						40	1	
						40	1	
					Avg	60	1	1

Appendix Table 1. Tensile Properties in the Warp Direction of Navy Shipboard Work Clothing Fabrics During Exposure at Various Bilateral Radiant Heat Flux Levels (continued)

Fabric Description	Radiant Heat Flux (cal/cm^2/sec)	Heater Temp (^{o}C)	Exposure Time (sec) At Start	Exposure Time (sec) At Rupture		Modulus (lb/inch width/ unit strain)	Rupture Load (lbs/inch width)	Strength Retention (%)
Fabric #18 (cont)	0.25	400	0	4		1920	73	
100% cotton FR						2050	77	
6.9 oz/sq yd						1880	72	
124 x 56					Avg	1950	74	72
			5	9		1310	41	
						1570	48	
						1630	49	
					Avg	1500	46	45
			10	13		1210	31	
						920	21	
						1380	33	
						1210	36	
						1350	31	
					Avg	1210	30	29
			20	--		0	0	0
	0.4	500	0	4		1690	58	
						1690	57	
						1590	54	
					Avg	1660	56	54
			5	7		90	2	
						80	2	
						40	1	
						20	1	
						30	1	
						80	2	
						50	1	
					Avg	50	1	1
	0.5	560	0	4		1290	36	
						1110	37	
						1010	32	
						1010	29	
						1060	36	
					Avg	1090	34	33
			5	--		0	0	0

Appendix Table 2. Time to Ignition for Navy Shipboard Work Clothing Exposed to Bilateral Radiant Heat

Fabric Description	Radiant Heat Flux (cal/cm²/sec)	Heater Temp (°C)	Time to Ignition (sec)	Smoke Generation
Fabric #1 35/65 polyester/cotton 10.3 oz/sq yd 70x44	0.2	350	No ignition, 2 min	No smoke generation
	0.25	400	No ignition, 2 min	No smoke generation
	0.4	500	25 27 28 Avg 27	Heavy smoking starting 10-15 seconds
	0.5	560	9 10 9 Avg 9	Heavy smoking approximately 2 seconds before ignition
	0.6	600	5 6.5 4 6.5 4 8 Avg 5.5	Heavy smoking
	0.7	650	5 5 5 6 4 Avg 5	Heavy smoking
Fabric #2 55/45 polyester/wool 6.4 oz/sq yd 62 x 52	0.2	350	No ignition, 2 min	No smoke generation
	0.25	400	No ignition, 2 min	No smoke generation
	0.4	500	Glow 90 65 85 Avg 80	Heavy smoke starting at 7-10 seconds; melting and intumescent char, 6-9 seconds
	0.5	560	Glow with Small Flame / Flame 25 21 / -- -- 24 50 / -- 52 18 25 / 22 26 19 25 / 21 26 20 23 / -- -- Avg 25 / 29	Heavy smoke, intumescent a char at 5 seconds
	0.6	600	Glow / Flame 9 / 18 12 / 16 13 / 15 11 / 18 11 / 13 Avg 11 / 16	Heavy smoke and melting starting at 3-5 seconds
	0.7	650	4 4 4 Avg 4	Medium smoke, intumescent char approximately 1 second before ignition

Appendix Table 2. Time to Ignition for Navy Shipboard Work Clothing
Exposed to Bilateral Radiant Heat (cont)

Fabric Description	Radiant Heat Flux ($cal/cm^2/sec$)	Heater Temp (^{o}C)	Time to Ignition (sec)	Smoke Generation
Fabric #3 100% cotton 10.3 oz/sq yd 68 x 42	0.2	350	No ignition, 2 min	No smoke generation
	0.25	400	Glow 31 37 37 27 39 27 29 Avg 32	Light smoke starting at 16 seconds
	0.4	500	Glow / Flame 10 22 10 15 12-15 -- 10 16 10 17 10-15 -- 12-15 -- 10-15 -- 8-10 14 9-11 14 Avg 10 16	Heavy smoke, approximately 2 seconds before ignition
	0.5	560	Glow / Flame 6 8 5 7 4 7 Avg 5 7	
	0.6	600	10* 4 10* 4 8* 4 8* 4 4 3 Avg 6	*Heavy smoke, approximately 2 seconds before ignition
	0.7	650	5 6 5 Avg 5	No smoke generation
Fabric #4 50/50 nylon/cotton 9.3 oz/sq yd 112 x 76	0.2	350	No ignition, 2 min	No smoke generation
	0.25	400	No ignition, 2 min	Light smoke at 50 seconds
	0.4	500	No ignition, 2 min	Heavy smoke starting at 5-8 seconds
	0.5	560	Glow with Small Flame 53 60 55 Avg 56	Heavy smoke at 4 seconds
	0.6	600	9 7 10 7 7 Avg 8	Heavy smoke approximately 1 second before ignition
	0.7	650	5 2 5 3 5 Avg 4	No smoke

Appendix Table 2. Time to Ignition for Navy Shipboard Work Clothing Exposed to Bilateral Radiant Heat (cont)

Fabric Description	Radiant Heat Flux ($cal/cm^2/sec$)	Heater Temp (^oC)	Time to Ignition (sec)		Smoke Generation
Fabric #6 65/35 polyester/cotton	0.2	350	No ignition, 2 min		No smoke generation
7.0 oz/sq yd 84 x 56	0.25	400	No ignition, 2 min		Light smoke at 90 seconds
	0.4	500	No ignition, 2 min		Heavy smoke at 17 seconds
	0.5	560	Glow	Flame	Light smoke at 5 seconds
			--	5	
			--	7	
			--	5	
			--	6	
			--	5	
			--	7	
			22	29	
			20	32	Heavy smoke at 5 seconds
			20	27	
			Avg 21	14	
	0.6	600	Glow	Flame	
			13	20	
			14	22	Heavy smoke at 4 seconds
			12	--	
			--	4	
			--	5	
			--	5	
			--	4	Light smoke before ignition
			--	4	
			--	5	
			--	5	
			Avg 13	8	
	0.7	650	3		Light smoke <1 second before ignition
			3		
			3		
			Avg 3		
Fabric #7 50/50 polyester/cotton	0.2	350	No ignition, 2 min		No smoke generation
6.9 oz/sq yd 108 x 56	0.25	400	No ignition, 2 min		No smoke generation
	0.4	500	Glow		Light smoke starting at 10 seconds
			35	31	
			30	29	
			Avg 31		
	0.5	560	8		Heavy smoke, approximately 2 seconds before ignition
			8		
			8		
			Avg 8		
	0.6	600	5	4	No smoke generation
			5	4	
			4		
			Avg 4		
	0.7	650	4	3	No smoke generation
			4	2	
			3		
			4		

Appendix Table 2. Time to Ignition for Navy Shipboard Work Clothing Exposed to Bilateral Radiant Heat (cont)

Fabric Description	Radiant Heat Flux ($cal/cm^2/sec$)	Heater Temp (^{o}C)	Time to Ignition (sec)		Smoke Generation
Fabric #8	0.2	350	No ignition, 2 min		No smoke generation
75/25 polyester/wool					
6.4 oz/sq yd	0.25	400	No ignition, 2 min		No smoke generation; intumescent char at 15 seconds
52 x 44					
	0.4	500	Slight Glow		Heavy smoke, melting and intumescent char at 5 seconds
			--		
			90		
			90		
			Avg 90		
	0.5	560	Glow with Small Flame	Flame	Light smoke, melting, starting at 5-7 seconds
			40	--	
			25	33	
			31	--	
			20	--	
			39	--	
			35	90	
			34	--	
			Avg 32	62	
	0.6	600	Glow with Small Flame	Flame	Heavy smoke, melting, starting at 3-5 seconds
			15	--	
			20	--	
			25	--	
			20	27	
			17	--	
			12	15	
			14	16	
			14	--	
			--	7	
			11	--	
			Avg 13	13	
	0.7	650	Glow with Small Flame	Flame	Medium smoke, melting, starting at 3-4 seconds
			15	--	
			15	--	
			13	24	
			10	--	
			14	16	
			7	9	
			--	8	
			8	11	
			18	23	
			--	7	
			Avg 13	14	
Fabric #9	0.2	350	Melted, 18-20 secs		No smoke generation
100% polyester					
6.0 oz/sq yd	0.25	400	Melted, 10 seconds		No smoke generation
36 x 24					
	0.4	500	Melted, 5 seconds		No smoke generation
	0.5	560	Melted, 3 seconds		Light smoke at 3 seconds. Heavy smoke at 10 seconds.
	0.6	600	Melted, 3 seconds		Light smoke at 3 seconds. Heavy smoke at 8 seconds.
	0.7	650	Melted, 3 seconds		Light smoke at 3 seconds. Heavy smoke at 6 seconds.

Appendix Table 2. Time to Ignition for Navy Shipboard Work Clothing Exposed to Bilateral Radiant Heat (cont)

Fabric Description	Radiant Heat Flux ($cal/cm^2/sec$)	Heater Temp (^oC)	Time to Ignition (sec)	Smoke Generation
Fabric #10 65/35 polyester/rayon 5.9 oz/sq yd 56 x 48	0.2	350	No ignition, 2 min	Light smoke at 35 seconds
	0.25	400	No ignition, 2 min	Light smoke at 15 seconds
	0.4	500	Glow 72 74 105 Avg 84	Medium smoke at 6 seconds
	0.5	560	6 5 5 5 Avg 5	Medium smoke at 4 seconds
	0.6	600	4 4 4 4 Avg 4	Light smoke, <1 second before ignition
	0.7	650	3 3 3 Avg 3	Medium smoke <1 second before ignition
Fabric #11 50/50 polyester/cotton 3.5 oz/sq yd 72 x 46	0.2	350	No ignition, 2 min	No smoke generation
	0.25	400	No ignition, 2 min	Light smoke at 11 seconds
	0.4	500	No ignition, 2 min	Heavy smoke at 5 seconds
	0.5	560	5 4 5 Avg 5	Heavy smoke at 3 seconds
	0.6	600	4 3 3 Avg 3	Medium smoke at 1 second before ignition
	0.7	650	2 2 2 Avg 2	Light smoke at ignition

Appendix Table 2. Time to Ignition for Navy Shipboard Work Clothing Exposed to Bilateral Radiant Heat (cont)

Fabric Description	Radiant Heat Flux (cal/cm²/sec)	Heater Temp (°C)	Time to Ignition (sec)	Smoke Generation
Fabric #12	0.2	350	No ignition, 2 min	No smoke generation
65/35 polyester/cotton				
4.8 oz/sq yd	0.25	400	No ignition, 2 min	No smoke generation
92 x 72				
	0.4	500	Glow / Flame	Heavy smoke at 7 seconds
			-- / --	
			60 / 102	
			55 / 71	
			40 / 47	
			35 / 43	
			42 / 48	
			45 / 58	
			Avg 40 / 60	
	0.5	560	7	Light smoke 1 second before ignition
			8	
			7	
			Avg 7	
	0.6	600	5	Light smoke <1 second before ignition
			5	
			5	
			Avg 5	
	0.7	650	3	Light smoke <1 second before ignition
			3	
			3	
			Avg 3	
Fabric #13	0.2	350	Melted, 10-19 secs	No smoke generation
100% polyester				
6.0 oz/sq yd	0.25	400	Melted, 9-12 secs	No smoke generation
69 x 69				
	0.4	500	Melted immediately	No smoke generation
	0.5	560	Melted immediately	No smoke generation
	0.6	600	Melted immediately	No smoke generation
	0.7	650	Melted immediately	Light smoke before melting
Fabric #14	0.2	350	No ignition, 2 min	Light smoke at 50 seconds
100% wool				
8.4 oz/sq yd	0.25	400	No ignition, 2 min	Medium smoke at 30 seconds, intumescent chart
56 x 50				
	0.4	500	Glow	Medium smoke at 6 seconds; Heavy smoke, intumescent char at 10 seconds
			53	
			70	
			60	
			Avg 61	
	0.5	560	Glow with Small Flame	Heavy smoke, intumescent char at 7-9 seconds
			25	
			40	
			39	
			35	
	0.6	600	Glow with Small Flame / Flame	Heavy smoke, intumescent char at 7 seconds
			32 / --	
			22 / 32	
			21 / 21	) small burst that self-extinguished after 1 second
			23 / 25	)
			15 / 27	
			21 / 27	

Appendix Table 2. Time to Ignition for Navy Shipboard Work Clothing Exposed to Bilateral Radiant Heat (cont)

Fabric Description	Radiant Heat Flux (cal/cm²/sec)	Heater Temp (°C)	Time to Ignition (sec)	Smoke Generation
Fabric #14 (cont) 100% wool 8.4 oz/sq yd 56 x 50	0.7	650	Glow / Flame 16 / 21 14 / 16 7 / 18 14 / 16 -- / 17 Avg 13 / 18	Heavy smoke, intumescent char at 5 seconds
Fabric #15 65/35 polyester/cotton 4.4 oz/sq yd 108 x 52	0.2	350	No ignition, 2 min	No smoke generation
	0.25	400	No ignition, 2 min	No smoke generation
	0.4	500	No ignition, 2 min	Medium smoke at 6 seconds
	0.5	560	6 6 20)------- 6 5 6 5 Avg 8	Light smoke at 4 seconds Heavy smoke at 4 seconds
	0.6	600	4 4 5 Avg 4	Light smoke 1 second before ignition
	0.7	650	3 3 3 Avg 3	Light smoke <1 second before
Fabric #16 65/35 polyester/cotton 5.8 oz/sq yd 125 x 54	0.2	350	No ignition, 2 min	No smoke generation
	0.25	400	No ignition, 2 min	No smoke generation
	0.4	500	Melted, >5 seconds	Light smoke starting at 5 seconds
	0.5	560	Glow / Flame 32 / 6 6 23* / 6 6 12 5 6 6 Avg 7	No smoke generation *Heavy smoke at 10 seconds
	0.6	600	Glow / Flame 19 / 4 4 16 / 5 5 4 3 6 2 Avg 4	Light smoke, 2-3 seconds before ignition
	0.7	650	1 3 3 2 3 Avg 2	No smoke

Appendix Table 2. Time to Ignition for Navy Shipboard Work Clothing Exposed to Bilateral Radiant Heat (cont)

Fabric Description	Radiant Heat Flux (cal/cm^2/sec)	Heater Temp ($^{\circ}$C)	Time to Ignition (sec)	Smoke Generation
Fabric #17	0.2	350	No ignition, 2 min	No smoke generation
95/5 Nomex/Kevlar				
4.6 oz/sq yd	0.25	400	No ignition, 2 min	Light smoke at 10 seconds
72 x 48				
	0.4	500	No ignition, 2 min	Medium smoke at 5 seconds
	0.5	560	No ignition, 2 min	Heavy smoke at 3-5 seconds
	0.6	600	Glow w/small flame	Medium smoke at 3-5 seconds
			83	
			65	
			68	
			Avg 72	
	0.7	650	Glow w/flame	Heavy smoke at 3 seconds
			18	
			17	
			17	
			Avg 17	
Fabric #18	0.2	350	No ignition, 2 min	Light smoke at 12 seconds
100% cotton, FR				
6.9 oz/sq yd	0.25	400	No ignition, 2 min	Medium smoke at 10 seconds
124 x 56				
	0.4	500	Flame	Heavy smoke at 6-7 seconds
			-- --	
			-- 11	
			-- --	
			11 --	
			Avg 11	
	0.5	560	6	Heavy smoke <1 second before ignition
			5	
			7	
			5	
			5	
			Avg 6	
	0.6	600	4	Light smoke <1 second before ignition
			4	
			4	
			Avg 4	
	0.7	650	4	Medium smoke at ignition
			3	
			3	
			Avg 3	
Fabric #19	0.2	350	No ignition, 2 min	No smoke generation
100% cotton				
3.6 oz/sq yd	0.25	400	No ignition, 2 min	No smoke generation
33 x 48				
	0.4	500	14	Medium smoke at 9-10 seconds
			17	
			15	
			17	
			13	
			Avg 15	
	0.5	560	9	Medium smoke at 8 seconds
			10	
			9	
			Avg 9	

Appendix Table 2. Time to Ignition for Navy Shipboard Work Clothing Exposed to Bilateral Radiant Heat (cont)

Fabric Description	Radiant Heat Flux ($cal/cm^2/sec$)	Heater Temp (^oC)	Time to Ignition (sec)	Smoke Generation
Fabric #19 (cont) 100% cotton 3.6 oz/sq yd 33 x 48	0.6	600	6 5 6 Avg 6	Light smoke <1 second before ignition
	0.7	650	3 2 4 Avg 3	No smoke
Fabric #20 65/35 polyester/cotton 3.4 oz/sq yd 32 x 32	0.2	350	No ignition, 2 min	No smoke generation
	0.25	400	No ignition, 2 min	No smoke generation
	0.4	500	No ignition, 2 min	Light smoke at 16 seconds
	0.5	560	7) 8) ------ 16) 15)	Light smoke <1 second before ignition
			--) --) ------ --) --) Avg 11	Heavy smoke at 8-10 seconds
	0.6	600	7 6 7 Avg 7	Light smoke <1 second before ignition
	0.7	650	8 5 4 3 2 Avg 4	Light smoke 1 second before ignition
Fabric #21 100% cotton 3.2 oz/sq yd 86 x 80	0.2	350	No ignition, 2 min	No smoke generation
	0.25	400	No ignition, 2 min	No smoke generation
	0.4	500	No ignition, 2 min	Medium smoke at 5 seconds
	0.5	560	5 4 5 Avg 5	Medium smoke <1 second before ignition
	0.6	600	3 3 3 Avg 3	Light smoke <1 second before ignition
	0.7	650	2 2 1 Avg 2	No smoke

Appendix Table 2. Time to Ignition for Navy Shipboard Work Clothing Exposed to Bilateral Radiant Heat (cont)

Fabric Description	Radiant Heat Flux (cal/cm^2/sec)	Heater Temp ($^{\circ}$C)	Time to Ignition (sec)	Smoke Generation
Fabric #22 65/35 polyester/cotton 3.0 oz/sq yd 144 x 144	0.2	350	No ignition, 2 min	No smoke generation
	0.25	400	No ignition, 2 min	No smoke generation
	0.4	500	No ignition, 2 min	Medium smoke at 7 seconds
	0.5	560	5 4 4 Avg 4	Medium smoke <1 second before ignition
	0.6	600	3 3 3 Avg 3	Light smoke <1 second before ignition
	0.7	650	2 1 2 Avg 2	Light smoke during flaming

Appendix Table 3. Heat Transfer from Outerwear Fabrics Exposed to Various Radiant Heat Flux Levels

Fabric No.	Incident Radiant Heat Flux ($cal/cm^2/sec$)	Time (sec)	Radiant Heat Transfer (%)	Fabric Event Description
13	0.40	11, 9, 10	60, 60, 62	Initial peak
100% polyester		16, 10, 16	69, 52, 93	Melts and drips
6.0 oz sq yd		22, 13, 14	133, 69, 102	Maximum heat transfer
		29, 25, 20	100, 100, 100	Completely melted
	0.75	5, 5, 6	29, 46, 44	Melts and drips
		7, 9, 7	99, 96, 94	Maximum heat transfer
		12, 16, 10	100, 100, 100	Completely melted
	1.25	3, 3, 3	23, 18, 100	Melts and drips
		4, 3, 4	127, 26, 148	Maximum transfer at ignition
9	0.40	9, 6, 6	64, 64, 50	Initial peak
100% polyester		12, 12, 12,	45, 54, 52	Melts and drips
6.0 oz/sq yd		16, 13, 15	121, 90, 93	Maximum heat transfer
		25, 20, 22	100, 100, 100	Totally melted
	0.75	--, 3, 3	---, 39, 27	Initial peak
		5, 5, 5	45, 23, 64	Melts, drips, and smokes
		7, 7, 7	96, 97, 97	Maximum heat transfer
		12, 12, 8	100, 100, 100	Completely melted
	1.25	2, 2, 2	21, 30, 25	Melts drips and smokes
		4, 3, 3	135, 100, 81	Ignition
6	0.40	3, 4, --	31, 38, 43	Initial peak
65/35 poly/cotton		25, 25, 25	62, 69, 79	Heat transfer stabilizes
7.0 oz/sq yd				
	0.75	15, 14, 6	67, 67, 56	Light smoke
		40, 40, 40	72, 83, 75	Heat transfer stabilizes
	1.25	3, 3, 3	29, 37, 29	Initial peak
		6, 5, 5,	36, 35, 33	Ignition
16	0.40	6, 9, 10	64, 83, 76	Initial peak
65/35 poly/cotton		20, 30, 25	74, 69 74	Heat transfer stabilizes, light-medium smoke
5.8 oz/sq yd				
	0.75	3, 4, 4	36, 56, 54	Initial peak
		8, 12, 10	183, 125, 69	Medium smoke, ignition
	1.25	3, 3, 3	36, 24 37	Initial peak
		4, 4, 4	30, 33, 28	Ignition
12	0.40	--, --, 5	--, --, 48	Initial peak
65/35 poly/cotton		7, 7, --	57, 50, --	Second peak
4.8 oz/sq yd		16, 22, 10	74, 74, 86	Heat transfer stabilizes
	0.75	6, 5, 3	60, 46, 32	Initial peak
		16, 17, 20	69, 60, 72	Heat transfer stabilizes
	1.25	3, 2, 2	31, 31, 24	Initial peak
		5, 5, 5	49, 50, 49	Ignition
15	0.40	10, 10, 11	38, 43, 43	Initial peak
65/35 poly/cotton		45, 60, 40	53, 48, 45	Heat transfer stabilizes
4.4 oz/sq yd				
	0.75	4, 5, 5	35, 64, 40	Initial peak
		13, 13, 10	77, 77, 72	Second peak
		--, --, 25	--, --, 72	Heat transfer stabilizes
		40, 35, --	100, 89, --	Glow
	1.25	4, 4, 4	69, 54, 55	Ignition

Appendix Table 3. Heat Transfer from Outerwear Fabrics Exposed to Various Radiant Heat Flux Levels (continued)

Fabric No.	Incident Radiant Heat Flux ($cal/cm^2/sec$)	Time (sec)	Radiant Heat Transfer (%)	Fabric Event Description
7	0.40	2, 2, 2	20, 25, 20	Initial peak
50/50 poly/cotton		17, 25, 20	40, 50, 43	Second peak
6.9 oz/sq yd		40, 52, 31	60, 50, 53	Light smoke
		50, 60, 45	63, 53, 45	Heat transfer stabilizes
	0.75	5, 6, 10	45, 43, 48	Initial peak
		7, 7, 18	48, 88, 84	Heavy smoke
		12, 26, --	205, 304 --	Ignition
		--, --, 50	---, ---, 83	Heat transfer stabilizes
	1.28	2, 2, 2	22, 17, 17	Initial peak
		4, 4, 4,	64, 62, 54	Ignition
		7, 7, 8,	153, 88, 101	Maximum heat transfer
11	0.40	6, 6, 5	40, 45, 40	Initial peak
50/50 poly/cotton		13, 13, 15	45, 50, 50	Heat transfer stabilizes
3.5 oz/sq yd				
	0.75	3, 3, 3	37, 50, 46	Initial peak
		20, 30, 30	80, 77, 80	Heat transfer stabilizes
	1.25	2, 2, 2	71, 62, 44	Initial peak
		4, 3, 3	111, 115, 100	Ignition
1	0.40	3, 3, 3	30, 25, 45	Initial peak
35/65 poly/cotton		--, 35, --	--, 43, --	Heat transfer stabilizes
10.3 oz/sq yd		35, 45, 45	58, 43, 93	Heavy smoke
	0.75	3, 4, 3,	44, 37, 33	Initial peak
		22, 21, 14	71, 72, 79	Heavy smoke
		29, 25, 15	69, 71, 69	Ignition
		44, 37, 28	137, 128, 103	Maximum heat transfer
	1.25	2, 3, 2	30, 32, 26	Initial peak
		5, 5, 5	41, 49, 38	Ignition
		24, 5, 25	67, 49, 62	Maximum heat transfer
3	0.40	4, 3, 3	50, 93, 40	Initial peak
100% cotton		27, --, 53	69, --, 138	Medium smoke
10.3 oz/sq yd		43, 60, 53	81, 100, 138	Maximum heat transfer
	0.75	2, 2, 3	35, 32, 31	Initial peak
		11, --, --,	46, --, --	Medium smoke
		--, 18, 15	--, 83, 69	Heavy smoke
		--, 20, --	--, 111, --	Glow
		22, --, 21	74, --, 100	Ignition
	1.25	2, 2, 2	28, 32, 33	Initial peak
		5, 7, 7	41, 66, 72	Ignition
18	0.40	3, 3, 3	28, 33, 33	Initial peak
100% cotton FR		20, 20, 20	35, 38, 38	Light smoke
10.3 oz/sq yd		25, 25, 40	38, 40, 40	Heat transfer stabilizes
	0.75	2, 2, 2	37, 39, 47	Initial peak
		10, 13, 11	140, 149, 168	Heavy smoke
		25, 27, 27	77, 77, 77	Heat transfer stabilizes
	1.25	2, 2, 2	24, 44, 54	Initial peak
		4, 4, 4	80, 194, 140	Ignition, heavy smoke

Appendix Table 3. Heat Transfer from Outerwear Fabrics Exposed to Various Radiant Heat Flux Levels (continued)

Fabric No.	Incident Radiant Heat Flux (cal/cm^2/sec)	Time (sec)	Radiant Heat Transfer (%)	Fabric Event Description
8	0.40	7, 7, 4	25, 25, 25	Initial peak
75/25		12, 13, 12	30, 38, 40	Second peak, light smoke
6.4 oz/sq yd		27, 23, 22	68, 53, 68	Melts, heavy smoke
		30, 37, 40	63, 78, 63	Heat transfer stabilizes
	0.75	5, 5, 4	56, 45, 72	Initial peak
		19, 12, 13	113, 157, 65	Heavy smoke
		--, --, 35	--, --, 344	Ignition
		60, 60, --	121, 91, --	Maximum heat transfer
	1.25	2, 3, 5	44, 23, 40	Initial peak
		6, 6, 10	129, 57, 120	Ignition, heavy smoke
2	0.40	3, 2, 3	43, 31, 40	Initial peak
55/45 poly/wool		19, 28, 18	67, 59, 60	Second peak
6.4 oz/sq yd		45, 60, 35	67, 136, 121	Heavy smoke, melts
	0.75	2, 4, 4	43, 45, 52	Initial peak
		13, 15, 15	63, 103, 64	Melts, heavy smoke
		40, 25, 35	76, 80, 84	Heat transfer stabilizes
	1.25	3, 4, 4	25, 33, 35	Initial peak, heavy smoke
		13, 10, 7	111, 120, 37	Ignition
14	0.40	3, 3, 5	30, 23, 33	Initial peak
100% wool		30, 24, 31	68, 38, 65	Heavy smoke, intumesces
8.4 oz/sq yd		52, 37, 31	70, 55, 65	Maximum heat transfer
	0.75	3, 3, 3	44, 44, 35	Initial peak
		10, 12, 8	68, 41, 44	Heavy smoke, intumesces
		17, 20, 15	80, 49, 87	Maximum heat transfer
		32, 42, 25	61, 44, 52	Heat transfer stabilizes
	1.25	2, 2, 4	37, 39, 38	Initial peak
		6, 8, 6	40, 44, 42	Heavy smoke, intumesces
		16, 22, 20	25, 40, 31	Ignition
4	0.40	3, 3, 3	45, 48, 43	Initial peak
50/50 nylon/cotton		19, 20, 18	75, 80, 63	Second peak
9.3 oz/sq yd		26, 38, 37	65, 63, 53	Heat transfer stabilizes
	0.75	7, 7, 7	39, 32, 44	Initial peak
		16, 16, 17	65, 76, 74	Heavy smoke
		--, 20, 19	--, 96, 115	Ignition
		60, --, --	75, --, --	Maximum heat transfer
	1.25	3, 2, 3	28, 22, 27	Initial peak
		8, 8, 7	39, 33, 36	Ignition
10	0.40	2, 2, 2	38, 38, 43	Initial peak
65/35 poly/rayon		15, 20, 25	74, 62, 69	Heat transfer stabilizes
5.9 oz/sq yd		40, 60, --	74, 71, --	Light smoke
	0.75	3, 6, 5	20, 35, 31	Initial peak
		9, 10, 11	34, 64, 30	Ignition, heavy smoke
	1.25	3, 3, 2	34, 33, 27	Initial peak
		5, 5, 3	46, 40, 45	Ignition
		5, 10, 3	46, 50, 45	Maximum heat transfer

Appendix Table 3. Heat Transfer from Outerwear Fabrics Exposed to Various Radiant Heat Flux Levels (continued)

Fabric No.	Incident Radiant Heat Flux ($cal/cm^2/sec$)	Time (sec)	Radiant Heat Transfer (%)	Fabric Event Description
17	0.40	3, 3, 3	24, 24, 36	Initial peak
95/5 Nomex/Kevlar		16, 16, 15	36, 36, 38	Heat transfer stabilizes
4.6 oz/sq yd				
	0.75	2, 3, 2	47, 49, 47	Initial peak
		15, 15, 10	79, 77, 88	Heat transfer stabilizes
	1.25	2, 2, 2	39, 26, 34	Initial peak
		6, 5, 5	83, 69, 67	Second peak, medium smoke
		35, 20, 20	79, 65, 62	Heat transfer stabilizes
		--, 50, 45	--, 65, 62	Ignition
19	0.40	2, 2, 2	40, 33, 33	Initial peak
100% cotton		22, 25, 18	64, 56, 66	Heat transfer stabilizes
3.6 oz/sq yd				
	0.75	5, 5, 4	78, 36, 61	Initial peak, medium smoke
		14, 9, 10	74, 83, 83	Ignition
	1.25	--, 1, 1	--, 26, 24	Initial peak
		2, 2, 2	41, 46, 46	Ignition
21	0.40	3, 3, 3	62, 60, 81	Initial peak
100% cotton		30, --, 15	71, --, 74	Light smoke
3.4 oz/sq yd		35, 16, 17	81, 74, 81	Heat transfer stabilizes
	0.75	3, 3, 5	60, 67, 67	Initial peak
		10, 8, 8	74, 72, 67	Light smoke
		15, 18, 15	79, 83, 78	Heat transfer stabilizes
	1.25	1, 2, 2	27, 41, 43	Initial peak
		4, 3, 4	166, 127, 71	Ignition
20	0.40	4, 4, 5	40, 49, 61	Initial peak
65/35 poly/cotton		11, --, --	85, --, --	Second peak
3.4 oz/sq yd		17, 18, --	78, 71, --	Heat transfer stabilizes, medium smoke
		--, --, 45	--, --, 100	Fabric destroyed
	0.75	3, 2, 3	32, 36, 33	Initial peak
		4, 4, 5	61, 58, 53	Heavy smoke
		12, 15, 13	113, 78, 143	Ignition
	1.25	2, 2, 2	30, 44, 26	Initial peak
		4, 3, 3	52, 53, 51	Ignition
22	0.40	--, 6, 6	--, 95, 67	Initial peak
65/35 poly/cotton		15, 15 --	79, 69, --	Light smoke
3.0 oz/sq yd		--, --, 26	--, --, 83	Medium smoke
		32, 45, 35	100, 100, 79	Fabric destroyed
	0.75	5, 5, 5	53, 58, 36	Initial peak, medium smoke
		8, 8, 10	124, 89, 93	Ignition
	1.25	2, 2, 2	30, 43, 26	Initial peak
		4, 3, 3	51, 52, 50	Ignition

Appendix Table 4. Temperature Rise in Skin Simulant Covered by Fabric Assembly During Flame Impingement (heat flux, 2.2 cal/cm^2/sec)

Outerwear Fabric No.	Outerwear Blend Ratio	Underwear Fabric No.	Underwear Blend Ratio (polyester/cotton)	Assembly Weight (oz/sq yd)	Assembly Thickness* (inch)		Temperature Rise (°C) at 3 sec	Temperature Rise (°C) at 6 sec	Maximum Temperature Rise (°C) 3 sec exp	Maximum Temperature Rise (°C) 6 sec exp
POLYESTER/COTTON BLENDS:										
13	100/0	single layer, outerwear fabric only		6.0	0.025		48.8	101.0	53.4	101.0
							51.0	102.4	56.8	102.4
							52.0	99.6	57.2	99.6
						Avg.	50.6	101.0	55.8	101.0
13	100/0	20	65/35	9.4	0.043		15.5	28.2	17.4	33.9
							12.4	34.2	15.1	36.7
							10.5	26.6	13.7	31.0
							--	30.0	--	32.3
							--	32.7	--	45.8
						Avg.	12.8	30.3	15.4	35.9
13	100/0	22	65/35	9.0	0.034		20.0	54.0	25.2	60.4
							26.0	45.8	31.5	50.0
							26.0	44.4	26.1	48.4
							23.2	44.0	28.1	48.4
							23.8	60.6	28.3	62.0
						Avg.	23.8	50.0	27.8	53.8
13	100/0	19	0/100	9.6	0.044		13.9	37.9	17.5	38.9
							13.0	35.7	16.6	36.6
							14.0	36.0	17.0	37.6
						Avg.	13.6	36.5	17.0	37.7
13	100/0	21	0/100	9.2	0.034		22.2	50.8	25.0	51.8
							21.5	52.0	26.7	53.6
							21.0	52.4	25.2	55.0
						Avg.	21.6	51.7	25.6	53.5
9	100/0	single layer, outerwear fabric only		6.0	0.035		47.0	100.4	49.4	107.4
							46.8	98.4	52.2	100.6
							46.4	95.0	48.2	95.8
						Avg.	46.7	97.9	49.9	101.3
9	100/0	20	65/35	9.4	0.053		10.9	31.4	16.9	25.6
							10.3	28.8	18.3	31.3
							11.4	31.2	14.4	44.6
							8.1	27.8	12.5	28.5
							7.9	37.0	15.6	40.3
						Avg.	9.7	31.2	15.5	34.1
9	100/0	22	65/35	9.0	0.044		19.0	50.2	23.1	54.3
							17.2	43.8	22.6	46.4
							23.4	52.0	21.9	54.0
							--	57.0	--	59.0
							--	57.7	--	59.0
						Avg.	19.9	52.1	22.5	54.5

*Measured at a pressure of 0.63 psi

Appendix Table 4. Temperature Rise in Skin Simulant Covered by Fabric Assembly During Flame Impingement (heat flux, 2.2 cal/cm^2/sec) (continued)

Outerwear Fabric No.	Outerwear Blend Ratio	Underwear Fabric No.	Underwear Blend Ratio (polyester/cotton)	Assembly Weight (oz/sq yd)	Assembly Thickness* (inch)		Temperature Rise (°C) at 3 sec	Temperature Rise (°C) at 6 sec	Maximum Temperature Rise (°C) 3 sec exp	Maximum Temperature Rise (°C) 6 sec exp
POLYESTER/COTTON BLENDS (cont):										
9	100/0	19	0/100	9.6	0.054		8.8	26.4	12.6	29.7
							11.1	28.3	14.6	32.5
							7.9	25.8	9.9	29.2
							10.5	--	15.9	--
							12.7	--	12.3	--
						Avg.	10.2	26.8	13.1	30.5
9	100/0	21	0/100	9.2	0.044		20.8	52.2	24.9	54.3
							17.6	52.2	24.8	55.1
							19.0	49.6	24.9	51.7
						Avg.	19.1	51.3	24.9	53.7
6	65/35	single layer, outerwear fabric only		7.0	0.016		27.2	48.4	32.4	51.0
							26.6	51.4	32.8	53.8
							26.0	49.2	31.4	53.6
						Avg.	26.6	49.7	32.2	52.8
6	65/35	22	65/35	10.0	0.025		16.8	36.7	23.1	40.9
							17.5	36.4	21.8	40.4
							16.7	36.8	22.9	41.0
						Avg.	17.0	36.6	22.6	40.8
6	65/35	21	0/100	10.2	0.025		16.7	35.6	23.8	41.0
							15.0	35.3	22.1	39.8
							15.6	34.0	22.2	38.6
						Avg.	15.8	35.0	22.7	39.8
16	65/35	single layer, outerwear fabric only		5.8	0.015		31.5	56.0	35.0	57.8
							31.5	54.4	33.2	57.2
							32.8	55.8	35.2	56.8
						Avg.	31.9	55.4	34.5	57.3
16	65/35	20	65/35	9.2	0.033		11.3	26.0	19.1	30.4
							10.8	26.1	18.9	31.2
							12.3	24.1	19.6	28.9
						Avg.	11.4	25.4	19.2	30.2
16	65/35	22	65/35	8.8	0.024		15.0	33.7	21.8	39.6
							15.5	33.0	21.3	41.1
							14.8	36.0	21.8	42.3
						Avg.	15.1	34.2	21.6	41.0
16	65/35	19	0/100	9.4	0.034		12.3	27.2	17.6	29.6
							13.7	25.8	18.4	29.5
							13.8	25.4	19.0	27.9
						Avg.	13.3	26.1	18.3	29.0

*Measured at a pressure of 0.63 psi

Appendix Table 4. Temperature Rise in Skin Simulant Covered by Fabric Assembly During Flame Impingement (heat flux, 2.2 cal/cm^2/sec) (continued)

Outerwear Fabric No.	Outerwear Blend Ratio	Underwear Fabric No.	Underwear Blend Ratio (polyester/cotton)	Assembly Weight (oz/sq yd)	Assembly Thickness* (inch)		Temperature Rise (°C) at 3 sec	Temperature Rise (°C) at 6 sec	Maximum Temperature Rise (°C) 3 sec exp	Maximum Temperature Rise (°C) 6 sec exp
POLYESTER/COTTON BLENDS (cont):										
16	65/35	21	0/100	9.0	0.024		13.8	35.5	23.5	41.3
							17.0	37.0	24.8	41.2
							14.8	35.5	25.3	39.7
						Avg.	15.2	36.0	24.5	40.9
12	65/35	single layer, outerwear fabric only		4.8	0.019		31.0	66.0	34.6	71.6
							30.5	72.0	32.7	75.0
							31.0	67.0	34.8	75.2
						Avg.	30.8	68.3	34.0	73.9
12	65/35	20	65/35	8.2	0.037		10.5	28.7	19.7	30.5
							11.0	26.6	19.9	28.3
							12.3	25.9	20.6	27.1
						Avg.	11.2	27.1	20.1	28.6
12	65/35	19	0/100	8.4	0.039		12.3	26.0	18.8	29.7
							13.0	25.2	18.8	29.0
							11.6	30.6	17.7	31.8
						Avg.	12.3	27.3	18.4	30.2
15	65/35	single layer, outerwear fabric only		4.4	0.012		29.8	48.0	31.8	59.2
							30.0	46.6	31.9	53.4
							27.7	49.6	30.4	57.0
						Avg.	29.2	48.1	31.4	56.5
15	65/35	20	65/35	7.8	0.030		8.7	26.8	19.7	28.2
							11.2	29.4	20.4	30.7
							11.8	26.8	21.7	27.9
						Avg.	10.6	27.7	20.6	28.9
15	65/35	19	0/100	8.0	0.031		11.0	26.8	17.8	28.3
							12.5	31.6	17.4	32.4
							12.4	30.2	18.3	31.7
							8.4	--	14.5	--
							12.8	--	17.6	--
						Avg.	11.4	29.5	17.1	30.8
Single layer, underwear fabric only	--	20	65/35	3.4	0.018		18.0 16.2	62.4 70.0	29.5 50.2	63.4 70.2
							19.0 21.0	38.0 34.8	35.2 50.3	63.4 70.2
							16.7 19.5	38.0 33.0	27.7 44.6	61.4 55.6
							15.0 18.5	42.6 38.8	29.7 38.1	41.8 55.0
							20.5 15.0	62.4 46.4	39.9 27.9	64.2 50.2
						Avg.	17.9	46.6	37.3	56.2
Single layer, underwear fabric only	--	22	65/35	3.0	0.009		32.6	62.8 63.0	36.3	64.6 65.6
							29.4	72.0 65.0	35.7	74.4 68.0
							29.6	62.0 69.0	35.1	65.2 74.6
							30.2	77.2 --	35.2	79.4 --
							32.5	82.4 --	37.1	83.8 --
						Avg.	30.9	69.2	35.9	72.0

*Measured at a pressure of 0.63 psi

Appendix Table 4. Temperature Rise in Skin Simulant Covered by Fabric Assembly During Flame Impingement (heat flux, 2.2 cal/cm^2/sec) (continued)

Outerwear Fabric No.	Outerwear Blend Ratio	Underwear Fabric No.	Underwear Blend Ratio (polyester/cotton)	Assembly Weight (oz/sq yd)	Assembly Thickness* (inch)		Temperature Rise (°C) at 3 sec	Temperature Rise (°C) at 6 sec	Maximum Temperature Rise (°C) 3 sec exp	Maximum Temperature Rise (°C) 6 sec exp
POLYESTER/COTTON BLENDS (cont):										
7	50/50	single layer, outerwear fabric only		6.9	0.012		24.4	35.8	26.6	42.2
							24.6	35.6	28.4	43.6
							25.6	39.6	27.6	46.2
						Avg.	24.9	37.0	27.5	44.0
7	50/50	22	65/35	9.9	0.028		16.8	36.0	23.3	41.5
							17.3	36.4	25.0	41.4
							16.4	36.4	23.3	42.0
							10.7	--	19.5	--
							17.0	--	23.5	--
						Avg.	15.6	36.3	22.9	41.7
7	50/50	21	0/100	10.0	0.028		21.3	38.0	23.3	43.7
							14.4	34.8	23.3	41.6
							15.3	37.2	24.0	43.1
						Avg.	17.0	36.7	23.5	42.8
11	50/50	single layer, outerwear fabric only		3.5	0.012		44.0	76.6	48.0	78.4
							40.0	74.0	45.2	76.8
							41.0	75.0	45.6	77.0
						Avg.	41.7	75.2	46.3	77.4
11	50/50	20	65/35	6.9	0.030		13.3	31.7	21.8	33.9
							12.0	30.5	20.1	32.2
							14.0	33.0	21.2	35.7
							--	32.1	--	34.6
							--	26.4	--	27.9
						Avg.	13.1	30.7	21.0	32.9
11	50/50	19	0/100	7.1	0.031		14.5	32.8	21.1	39.9
							13.4	33.8	19.0	34.2
							13.2	32.4	19.1	32.2
						Avg.	13.7	33.0	19.7	36.1
1	35/65	single layer, outerwear fabric only		10.3	0.030		13.6	24.8	20.8	40.6
							12.8	21.6	21.0	40.0
							12.8	25.2	20.4	38.8
						Avg.	13.1	23.9	20.7	39.8
1	35/65	22	65/35	13.3	0.039		9.0	24.2	17.9	35.2
							11.0	24.4	19.1	38.8
							9.7	18.8	16.3	37.0
						Avg.	9.9	22.5	17.8	37.0
1	35/65	21	0/100	13.5	0.039		10.4	19.3	18.8	39.6
							10.5	22.6	18.4	35.7
							10.1	23.5	18.0	40.0
						Avg.	10.3	21.8	18.4	38.4

*Measured at a pressure of 0.63 psi

Appendix Table 4. Temperature Rise in Skin Simulant Covered by Fabric Assembly During Flame Impingement (heat flux, 2.2 cal/cm^2/sec) (continued)

Outerwear Fabric No.	Outerwear Blend Ratio	Underwear Fabric No.	Underwear Blend Ratio (polyester/cotton)	Assembly Weight (oz/sq yd)	Assembly Thickness* (inch)		Temperature Rise (°C) at 3 sec	Temperature Rise (°C) at 6 sec	Maximum Temperature Rise (°C) 3 sec exp	Maximum Temperature Rise (°C) 6 sec exp
POLYESTER/COTTON BLENDS (cont):										
3	0/100	single layer, outerwear fabric only		10.3	0.029		14.3	26.8	18.3	32.2
							14.0	23.6	17.9	32.0
							14.7	26.6	17.9	35.2
						Avg.	14.3	25.7	18.0	33.1
3	0/100	22	65/35	13.3	0.038		12.4	23.2	15.4	35.4
							12.7	23.6	15.3	34.1
							11.3	20.8	15.4	34.9
						Avg.	12.1	22.3	15.4	34.8
3	0/100	21	0/100	13.5	0.038		11.1	22.7	16.6	30.1
							12.8	22.5	16.1	29.5
							12.0	26.0	17.0	33.9
						Avg.	12.0	23.7	16.6	31.2
18	0/100 FR treated	single layer, outerwear fabric only		6.9	0.018		21.6	52.4	26.4	53.2
							20.6	49.4	26.6	50.8
							21.0	52.6	26.8	53.6
							21.1	51.5	26.6	52.5
18	0/100	20	65/35	10.3	0.036		10.0	38.8	16.6	41.3
							11.2	35.8	18.9	39.2
							10.4	37.2	20.0	38.0
						Avg.	10.5	37.3	18.5	39.5
18	0/100	22	65/35	9.9	0.027		11.3	42.9	19.6	44.5
							12.1	44.7	20.0	46.7
							11.8	43.8	19.5	46.1
							11.7	43.8	19.7	45.8
18	0/100	19	0/100	10.5	0.037		12.4	38.4	16.2	41.9
							10.8	39.6	15.9	42.0
							11.9	37.3	16.8	41.7
						Avg.	11.7	38.4	16.3	41.9
18	0/100	21	0/100	10.1	0.027		12.2	42.0	19.8	45.0
							11.8	43.6	18.2	44.8
							12.9	41.1	20.9	42.9
						Avg.	12.3	42.2	19.6	44.2

*Measured at a pressure of 0.63 psi

Appendix Table 4. Temperature Rise in Skin Simulant Covered by Fabric Assembly During Flame Impingement (heat flux, 2.2 cal/cm^2 sec) (continued)

Outerwear Fabric No.	Outerwear Blend Ratio	Underwear Fabric No.	Underwear Blend Ratio (polyester/cotton)	Assembly Weight (oz/sq yd)	Assembly Thickness* (inch)		Temperature Rise (°C) at 3 sec	Temperature Rise (°C) at 6 sec	Maximum Temperature Rise (°C) 3 sec exp	Maximum Temperature Rise (°C) 6 sec exp
POLYESTER/COTTON BLENDS (cont):										
Single layer, underwear fabric only	--	19	0/100	3.6	0.019		23.6	38.8 42.0	30.0	41.8 44.0
							26.0	43.0 42.4	29.7	45.2 45.4
							24.0	45.0 --	29.7	47.0 --
						Avg.	24.5	42.4	29.8	44.7
Single layer, underwear fabric only	--	21	0/100	3.2	0.009		33.7	75.0	37.6	77.2
							32.0	82.4	34.4	80.6
							29.5	80.0	34.0	82.6
							--	80.0	--	84.2
							--	79.6	--	81.8
						Avg.	31.7	79.4	35.3	81.3
POLYESTER/WOOL BLENDS										
8	75/25	single layer, outerwear fabric only		6.4	0.018		25.7	52.0	27.1	56.2
							24.6	68.0	26.7	72.2
							24.2	68.0	26.7	74.2
						Avg.	24.8	62.7	26.8	67.5
8	75/25	20	65/35	9.8	0.036		10.1	22.5	18.1	29.2
							9.8	24.8	17.2	29.6
							9.9	25.2	18.0	26.9
						Avg.	9.9	24.2	17.8	28.6
8	75/25	22	65/35	9.4	0.027		14.0	40.8	27.0	41.4
							14.7	43.5	24.2	45.3
							15.3	38.4	22.5	40.4
						Avg.	14.7	40.9	24.6	42.4
8	75/25	19	0/100	10.0	0.037		9.9	24.5	17.0	29.1
							11.5	24.6	16.3	30.2
							11.0	22.7	17.4	28.6
						Avg.	10.8	23.9	16.9	29.3
8	75/25	21	0/100	9.6	0.027		13.5	41.6	22.7	49.7
							14.8	41.0	24.0	46.0
							15.9	42.2	24.3	46.2
						Avg.	14.7	41.6	23.7	47.3
2	55/45	single layer, outerwear fabric only		6.4	0.019		22.4	52.0	29.8	58.2
							23.2	41.2	31.0	49.0
							23.0	40.8	31.6	48.6
							--	44.6	--	48.6
							--	36.0	--	40.0
						Avg.	22.9	42.9	30.8	48.9

*Measured at a pressure of 0.63 psi

Appendix Table 4. Temperature Rise in Skin Simulant Covered by Fabric Assembly During Flame Impingement (heat flux, 2.2 cal/cm^2/sec) (continued)

Outerwear Fabric No	Outerwear Blend Ratio	Underwear Fabric No.	Underwear Blend Ratio (polyester/cotton)	Assembly Weight (oz/sq yd)	Assembly Thickness* (inch)		Temperature Rise (°C) at 3 sec	Temperature Rise (°C) at 6 sec	Maximum Temperature Rise (°C) 3 sec exp	Maximum Temperature Rise (°C) 6 sec exp
POLYESTER/WOOL BLENDS (cont):										
2	55/45	22	65/35	9.4	0.028		15.2	35.0	22.8	42.0
							15.8	33.2	25.4	41.9
							15.7	31.4	26.2	40.5
						Avg.	15.6	33.2	24.8	41.5
2	55/45	21	0/100	9.6	0.028		13.8	31.4	23.2	38.9
							14.5	33.8	22.3	42.3
							14.2	33.4	23.3	40.8
						Avg.	14.2	32.9	22.9	40.7
14	0/100	single layer, outerwear fabric only		8.4	0.041		11.8	26.5	15.5	29.0
							13.0	25.0	15.8	28.3
							12.0	26.4	15.2	28.5
						Avg.	12.3	26.0	15.5	28.6
14	0/100	20	65/35	11.8	0.059		8.3	16.0	11.7	18.7
							8.8	16.5	11.8	19.0
							8.5	15.9	11.8	18.0
						Avg.	8.5	16.1	11.8	18.6
14	0/100	22	65/35	11.4	0.050		10.3	20.0	12.7	21.8
							15.4	18.5	13.4	21.9
							9.6	19.6	12.8	22.3
						Avg.	11.8	19.4	13.0	22.0
14	0/100	19	0/100	12.0	0.060		7.3	15.8	11.4	18.2
							8.3	16.2	12.0	18.3
							8.3	16.2	12.0	18.5
						Avg.	8.0	16.1	11.8	18.3
14	0/100	21	0/100	11.6	0.050		11.3	18.9	14.0	21.2
							10.3	18.1	13.6	20.8
							10.3	19.3	13.8	22.2
							10.6	18.8	13.8	21.4
OTHER BLENDS:										
4	50/50 nylon/cotton	single layer, outerwear fabric only		9.3	0.020		23.0	38.2	31.3	38.2
							23.0	40.2	31.1	40.6
							23.2	38.6	31.6	40.2
							23.1	39.0	31.3	39.7
4	50/50 nylon/cotton	22	65/35	12.3	0.029		11.7	23.3	19.8	25.5
							12.3	23.3	16.8	25.8
							11.8	23.0	20.8	25.8
						Avg.	11.9	23.2	19.1	25.7

*Measured at a pressure of 0.63 psi

Appendix Table 4. Temperature Rise in Skin Simulant Covered by Fabric Assembly During Flame Impingement (heat flux, 2.2 cal/cm^2/sec) (continued)

Outerwear Fabric No.	Outerwear Blend Ratio	Underwear Fabric No.	Underwear Blend Ratio (polyester/cotton)	Assembly Weight (oz/sq yd)	Assembly Thickness* (inch)		Temperature Rise (°C) at 3 sec	Temperature Rise (°C) at 6 sec	Maximum Temperature Rise (°C) 3 sec exp	Maximum Temperature Rise (°C) 6 sec exp
OTHER BLENDS (cont):										
4	50/50	21	0/100	12.5	0.029		10.4	19.4	15.3	27.3
							10.1	14.8	15.2	26.1
							8.7	15.8	14.9	24.7
						Avg.	9.7	17.8	15.1	26.0
10	55/35 polyester/ rayon	single layer, outerwear fabric only		5.9	0.017		26.4	47.2	30.4	57.2
							25.6	48.0	31.2	57.2
							23.6	47.2	29.3	53.4
							25.2	47.5	30.3	55.9
10	55/35 polyester/ rayon	20	65/35	9.3	0.035		11.8	24.6	17.4	32.6
							11.5	23.4	16.8	31.5
							11.7	26.5	18.6	34.0
							11.7	24.8	17.6	32.7
10	55/35 polyester/ rayon	19	0/100	9.5	0.036		15.3	27.9	19.9	37.1
							13.2	27.3	18.4	40.6
							13.3	27.8	19.1	37.2
						Avg.	13.9	27.7	19.1	38.3
NOMEX T456:										
17	95/5 Nomex/Kevlar	single layer, outerwear fabric only		4.6	0.015		29.6	65.6	34.8	69.2
							26.8	61.2	34.4	67.8
							30.8	62.8	37.3	68.0
						Avg.	29.1	63.2	35.5	68.3
17	95/5 Nomex/Kevlar	20	65/35	8.0	0.033		18.7	40.3	26.4	46.1
							16.8	39.4	26.5	45.3
							16.8	38.8	25.2	42.3
							17.4	39.5	26.0	44.6
17	95/5 Nomex/Kevlar	22	65/35	7.6	0.024		20.0	51.0	30.9	55.8
							21.3	55.8	32.0	55.8
							22.6	50.6	32.1	57.0
						Avg.	21.3	52.9	31.7	56.2
17	95/5 Nomex/Kevlar	19	0/100	8.2	0.034		14.3	35.7	25.6	42.3
							12.1	35.8	22.3	42.2
							15.2	36.4	23.0	43.1
						Avg.	14.9	36.0	23.5	42.5
17	95/5 Nomex/Kevlar	21	0/100	7.8	0.024		19.9	52.0	28.6	57.2
							20.8	50.2	30.4	54.6
							20.6	50.8	29.4	55.2
						Avg.	20.4	51.0	29.5	55.7

*Measured at a pressure of 0.63 psi